50m Research Vessel Design
Seakeeping Analysis

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Executive Summary

Glosten analyzed the seakeeping performance of the MBARI new vessel (MNV) design at the normal science loading condition using SMP, a linear potential flow theory seakeeping analysis software. Global vessel motions, point motions and accelerations, motion sickness incidence (MSI), and motion induced interruptions were computed for Sea States 3, 4 and 5. Waves were assumed to be long-crested (single-directional) in this analysis for conservative estimates of vessel motions.

The MNV is equipped with a Quantum *MAGLift ML380* active roll stabilization system to decrease roll motions at both the zero-speed and underway conditions. The SMP model of *ML380* was developed based on the modeling information provided by Quantum, and the list coefficient was tuned to match the roll reduction performance predicted by Quantum (Reference 7).

Glosten found that the MNV motions meet most of the basic design requirements at the sea states selected for this analysis. Some of the conclusions are summarized as follows:

- Pitch motions are less than 2 degrees (RMS) at Sea States 3 and 4
- Roll motions are less than 3 degrees (RMS) at Sea States 3 and 4
- Vertical accelerations at Main Deck amidships at deck edge are less than 0.15g (RMS) at Sea States 3, 4 and 5
- Lateral accelerations at Main Deck amidships at deck edge are less than 0.05g (RMS) at Sea States 3, 4 and 5
- MSI in the Control Room and Wet Lab is less than 20% (in two hours) at Sea States 3, 4 and 5.
- MSI in the Pilothouse is less than 20% at Sea States 3 and 4, but will reach 25% in oblique seas at Sea State 5

Modeling

The US Navy Ship Motion Program (SMP, Reference 1) was used to analyze the vessel. SMP calculates a vessel's seakeeping responses in the frequency domain using linear strip theory. The vessel is treated as a three-dimensional rigid body with freedom to translate and rotate about its three axes. The position, velocity, and acceleration of any point on the vessel can be calculated from this information.

Sea States Definition

Some of the seakeeping results are presented in terms of specific standard sea states. Standard sea state definitions are as given in Reference 2, and are shown here in Figure 1. The sea states of interest, Sea States 3 through 5, are highlighted.

TABLE F-1 – NATO SEA STATE NUMERAL TABLE FOR THE OPEN OCEAN NORTH ATLANTIC

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (sec)	
	Range	Mean	Range	Mean		Range**	Most Probable***
0 – 1	0 – 0.1	0.05	0 - 6	0.5	0	–	–
2	0.1 – 0.5	0.3	7 - 10	3.5	7.2	3.3 – 12.8	7.5
3	0.5 – 1.25	0.88	11 - 16	8.5	22.4	5.0 – 14.8	7.5
4	1.25 – 2.5	1.88	17 - 21	19	28.7	6.1 – 15.2	8.8
5	2.5 – 4	3.25	22 - 27	24.5	15.5	8.3 – 15.5	9.7
6	4 – 6	5	28 - 47	37.5	18.7	9.8 – 16.2	12.4
7	6 – 9	7.5	48 - 55	51.5	6.1	11.8 – 18.5	15.0
8	9 – 14	11.5	56 - 63	59.5	1.2	14.2 – 18.6	16.4
>8	>14	>14	>63	>63	<0.05	15.7 – 23.7	20.0

*Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1 (H_2/19.5)^{1/7}$

**Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

***Based on periods associated with central frequencies included in Hindcast Climatology.

Figure 1 NATO STANAG sea state definitions (reproduced from Reference 2)

The exact definitions of Sea State 3 through 5 used in this analysis are provided in Table 1.

Table 1 Climatology for seakeeping analysis

	Sea State 3	Sea State 4	Sea State 5
Wave significant height (H_S, ft)	2.9	6.2	10.7
Wave peak period (T_P, s)	7.5	8.8	9.7

The sea states in Table 1 were modeled with Bretschneider spectra to simulate fully developed open-ocean conditions. Waves were assumed to be long-crested (single-directional) for this analysis; this means there is no wave spreading. The use of longcrested seas tends to overpredict pitch and underpredict roll in head seas. Conversely, in beam seas the roll motion tends to be overpredicted and pitch motions under predicted.

A Bretschneider spectrum of the form

$S_{ff}(\omega) = \frac{1.25}{4}\frac{\omega_0^4}{\omega^5}H_S^2 \exp\left[-1.25\left(\frac{\omega_0}{\omega}\right)^4\right]$ was chosen to represent the sea states,

where

H_S is significant wave height
ω_0 is modal wave frequency

Vessel Particulars

Figure 2 contains the body plan of the MNV design constructed for the SMP hull model based on Reference 4.

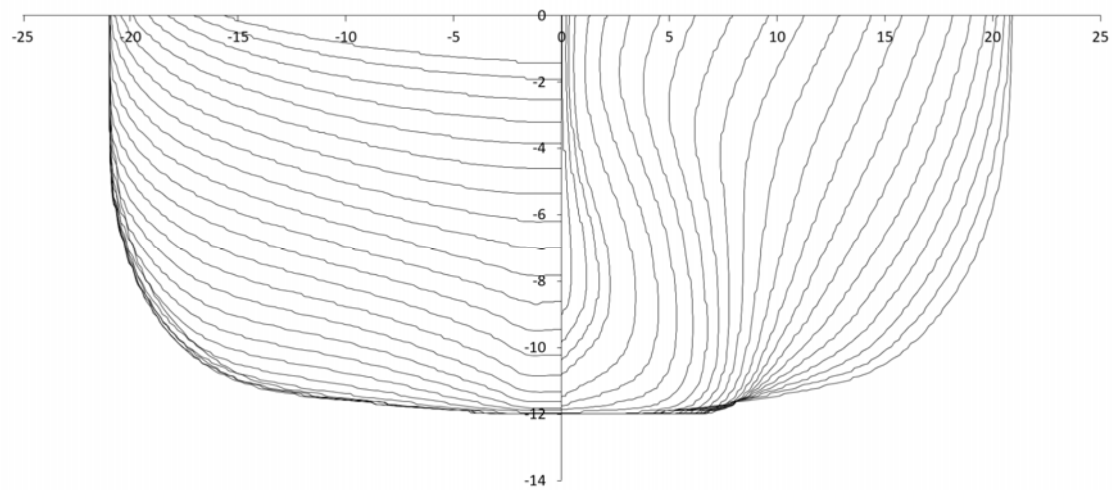


Figure 2 Body plan of MNV design (dimensions in ft.)

Vessel particulars and load condition used in this analysis are defined in Table 2. These conditions correspond to the "Normal Science Loading at Departure" condition (Reference 3).

Table 2 Vessel particulars and load conditions for seakeeping analysis

Parameter	Values
Displacement, LT	1,251
Length between perpendiculars	162.6
Draft, ft	12.0
Vertical center of gravity[1], ft	17.4
Transverse metacentric height[2], ft	4.62
Free-surface correction, ft	0.17
Roll gyradius[3] as a fraction of beam, nondimensional	0.38
Pitch gyradius[3] as a fraction of length[4], nondimensional	0.22
Yaw gyradius[3] as a fraction of length[4], nondimensional	0.22

1. Vertical location of the center of gravity above baseline (without free-surface correction).
2. Including free-surface correction.
3. Gyradius is calculated about the center of gravity for roll and yaw and about a point on the waterplane directly below the center of gravity for pitch.
4. Length between perpendiculars is used for this calculation.

Motion Points for Seakeeping Analysis

Seakeeping response was calculated at a series of points on the vessel. These points and their locations are shown in Table 3. The points were chosen to represent mission critical locations on the vessel. The ROV Launch Sheave, Stern A-Frame Sheave, and Main Crane tip were selected for evaluation of launch and recovery operations. The middle of the Pilothouse, Wet Lab, and Control Room were chosen as places where a person is likely to spend time doing work and would therefore be susceptible to performance degradation due to seasickness.

Table 3 Motion points for seakeeping analysis

Motion Point	L, ft aft Fr0 (ft)	T, ft stbd (ft)	V, ft ABL (ft)
ROV Launch Sheave	71.7	-33.2	29.9
Stern A-Frame Sheave	-12.9	0.0	38.3
Main Crane Tip (positioned at starboard side)	33.3	47.5	31.3
Middle of Pilothouse	123.3	0.0	48.4
Middle of Wet Lab	44.5	10.6	22.2
Middle of Control Room	89.6	-10.3	21.9

Interpreting Polar Plot of Seakeeping Results

Figure 3 shows an example polar plot. The values on the circumference indicate wave heading, as a direction 'from' in degrees. This means, for example, that a wave heading of 45 degrees indicates that the waves are approaching the vessel from the starboard bow. This convention is shown adjacent to the polar diagram.

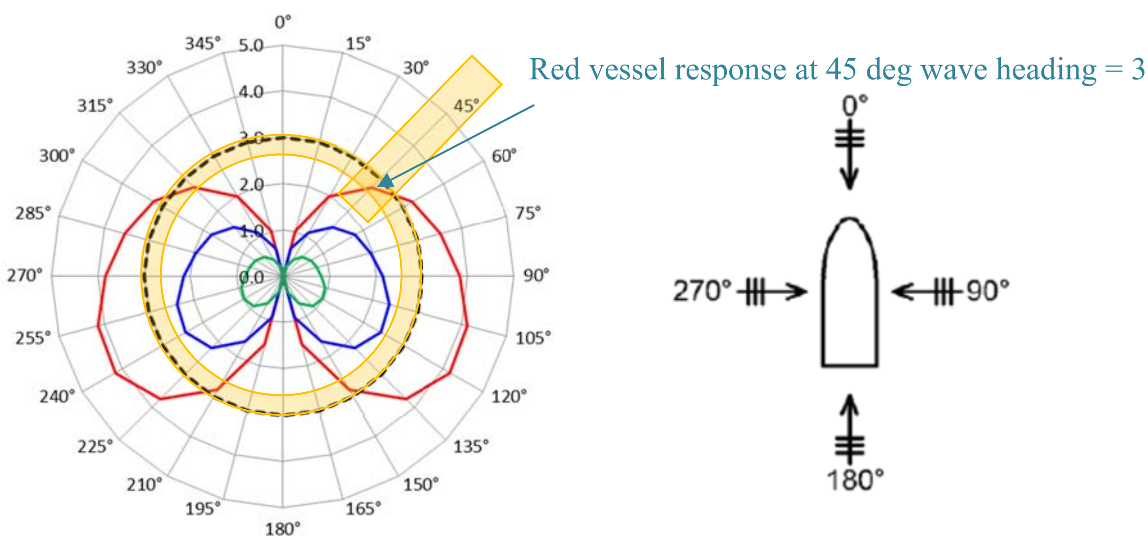


Figure 3 Example polar diagram with wave heading sign convention

Each colored line represents a response of a unique vessel or a unique sea state as a function of wave heading. For example, the red line shows that the response of a vessel in 45 degree waves is three response units. If the motion shown was roll angle, it would be three degrees of roll.

The dashed-black line at a constant response (over all headings) represents a criterion that must be met; in the example, the criterion is 3 response units. In the example plot, the green and blue lines show that the criteria are met in all wave headings, but the red lines show that the criteria are met only for head seas and following seas. Not all polar diagrams have a criterion indicated.

Active Roll Stabilizers

The MBARI vessel is equipped with active roll stabilization systems to decrease roll motions. The active roll stabilizer model used on MBARI is the Quantum *MAGLift ML380*. The stabilizer information was provided by Quantum (References 8, 9, 10) and the equivalent SMP model of the roll stabilizer was developed based on these documents. Table 4 contains the point where the stabilizer rotor axle centerline pierces the hull and it also contains the anhedral angle that defines the orientation of the rotors. Figure 4 shows the roll stabilizer rotors fully extended.

Table 4 Roll stabilizer axle centerline pierce point and orientation

LCA[1] (ft)	TCA[2] (ft)	VCA[3] (ft)	Anhedral[4] (deg)
92.1	15.6	2.2	10.0

[1]Longitudinal coordinate of the axle centerline where it pierces the hull shell, positive forward from Frame 0.
[2]Transverse coordinate of the axle centerline where it pierces the hull shell, positive port from the centerplane.
[3]Vertical coordinate of the axle centerline where it pierces the hull shell, positive up from the baseplane.
[4]Angle of axle relative to a horizontal plane parallel to the baseplane, positive downward.

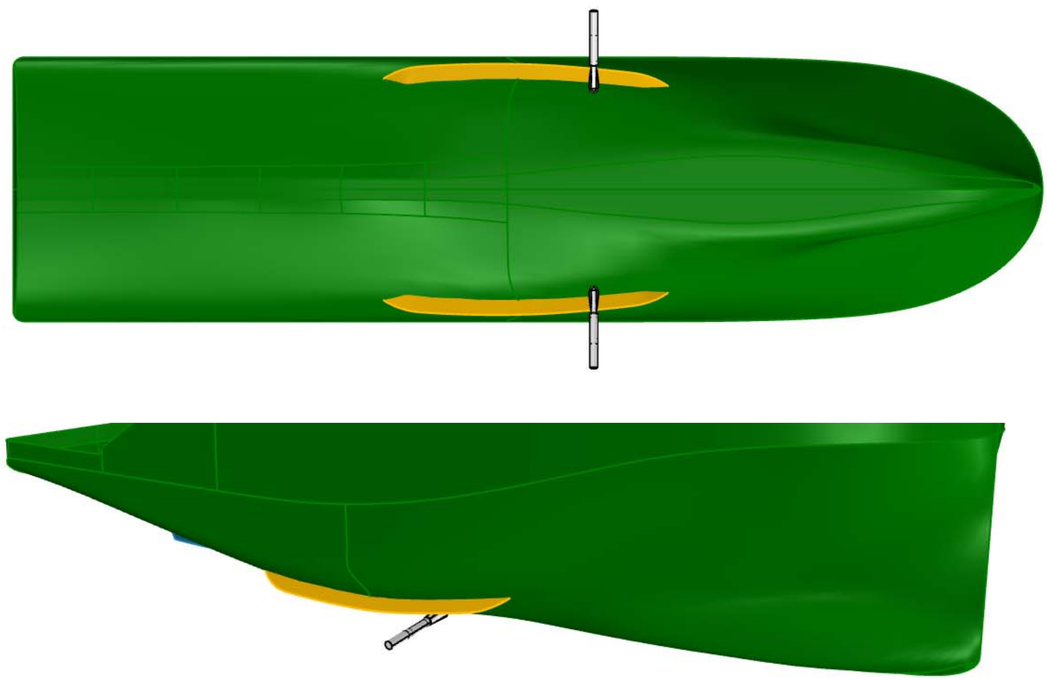


Figure 4 MNV model with roll stabilizers extended

Table 5 contains particulars of *MAGLift ML380* roll stabilizer rotors, including the target rotor speeds and the maximum lift coefficient estimated at zero ship speed based on information from Quantum (Reference 8).

The initial SMP prediction results indicated that the roll motion reduction is overpredicted compared to the performance prediction by Quantum (Reference 7). So, the equivalent lift coefficient in the SMP stabilizer model was adjusted to match the percentage reduction in roll motion predicted by Quantum for beam seas at Sea State 5 (Reference 7).

Table 5 Roll stabilizer (*MAGLift ML380*) particulars and target operational conditions at zero-speed

Rotor Span (ft)	Rotor Diameter (ft)	Area[1] (ft^2)	Rotor Rotational Speed at Zero-speed (RPM)	Rotor Sweep Speed at Zero-speed (deg/s)	Max. Lift Coefficient[2]
8.7	1.25	10.8	450	53	4.2

[1]Projected area of one stabilizer rotor
[2]Estimated maximum lift coefficient at maximum rotor speed (from Quantum, Reference 8)

Quantum was not able to provide the full control coefficients for *MAGLift ML380* control systems, so some of the control coefficients were estimated based on Cox and Lloyd (Reference 11) and Lloyd (Section 12.9 of Reference 12), which offer overviews of fin stabilizer control systems and methods for calculating their coefficients, respectively.

Figure 5 shows the vessel roll displacements (in polar diagrams) for the vessel variants, with and without the active roll stabilizers operating. The heave and pitch motions are not affected much by the roll stabilizers. The estimated reduction in RMS roll displacement at beam seas (at the worst wave headings: 105 degree or 240 degree) is approximately 37%, 35%, and 32% at Sea State 3, 4 and 5, respectively.

Figure 6 shows the vertical displacements (in polar diagrams) at ROV Launch Sheave for the vessel variants, with and without the active roll stabilizers operating. Figure 7 shows the vertical displacements (in polar diagrams) at Main Crane tip for the vessel variants, with and without the active roll stabilizers operating. The RMS vertical displacement at ROV Launch Sheave and Main Crane tip can be reduced by approximately 13% and 17%, respectively in Sea State 5 (at the worst wave heading).

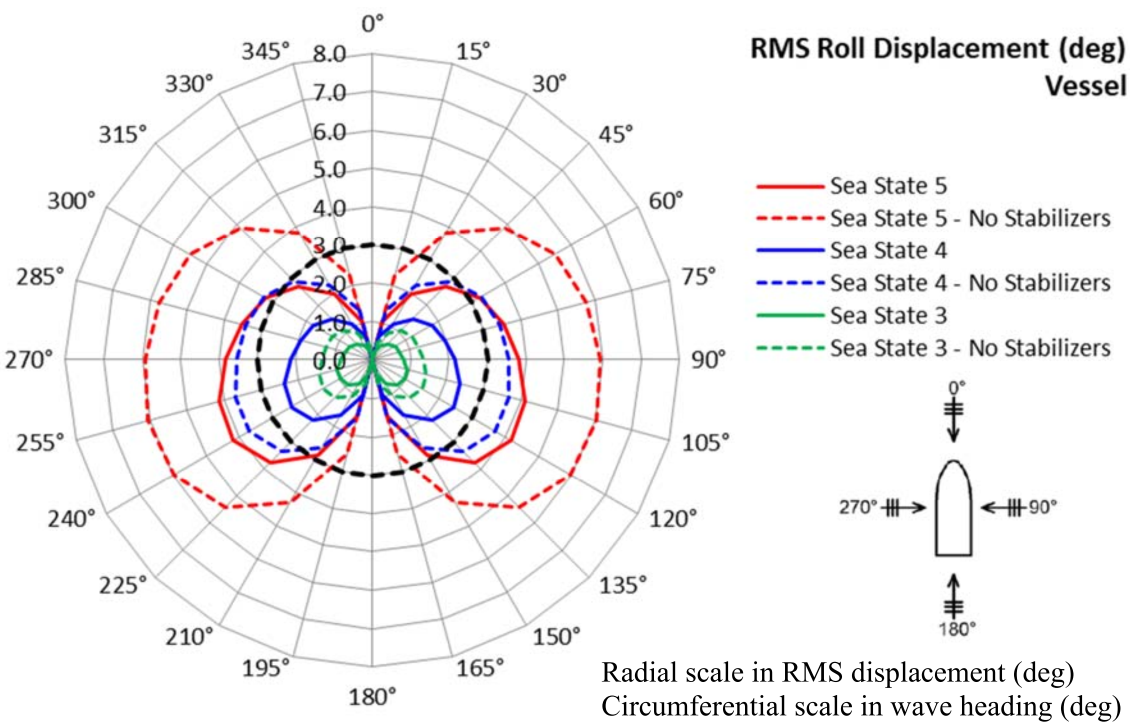


Figure 5 RMS roll displacement at vessel in Sea States 3 through 5 – with and without the active roll stabilizers operating

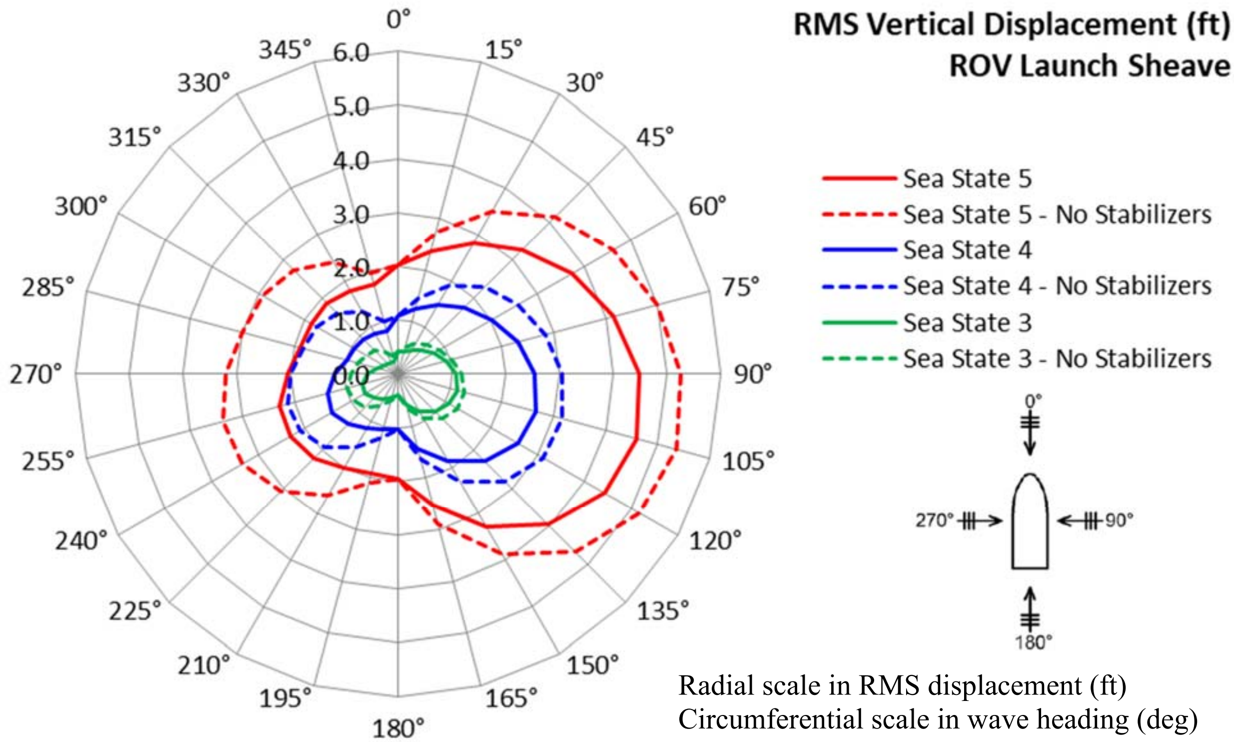


Figure 6 RMS vertical displacement at ROV Launch Sheave in Sea States 3 through 5 – with and without the active roll stabilizers operating

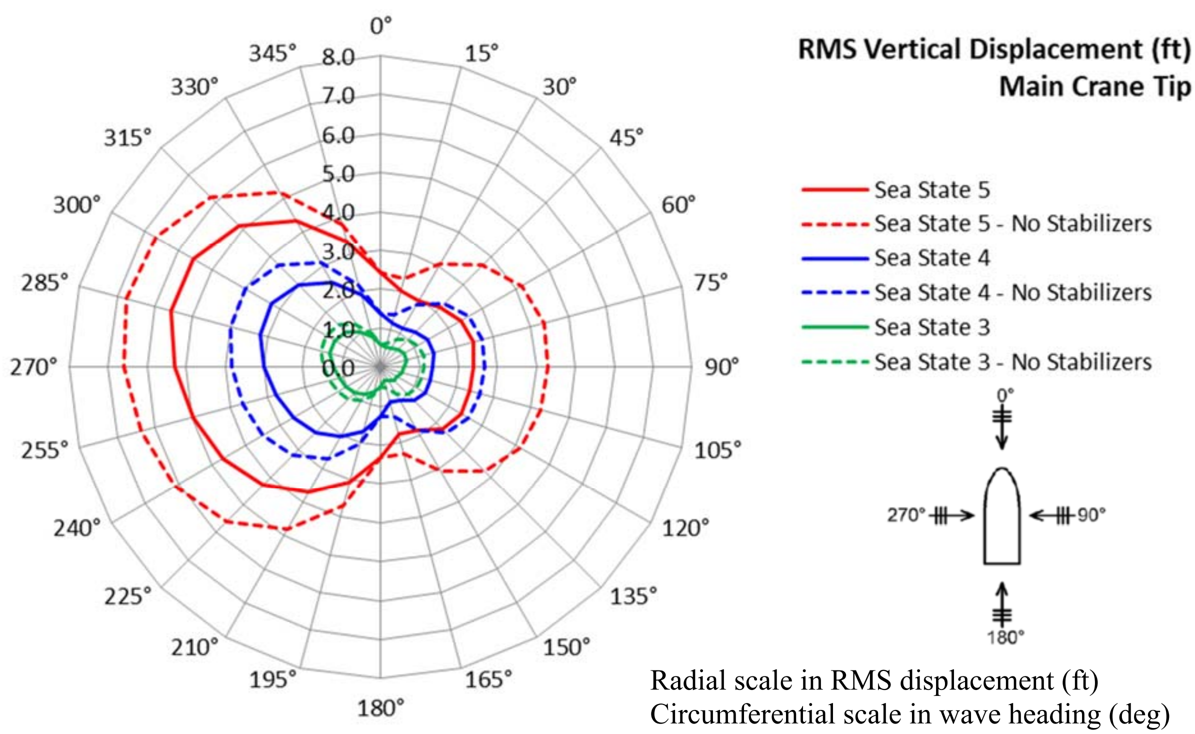


Figure 7 RMS vertical displacement at Main Crane tip in Sea States 3 through 5 – with and without the active roll stabilizers operating

Bilge Keels

The bilge keel extends from Frame 30 to 53 (Reference 5) as shown in Figure 4. Table 6 contains the full-length bilge keel particulars. All sets of seakeeping results presented in this report are for the vessel with the full-length bilge keel installed unless noted otherwise.

Table 6 Full-length bilge keels particulars (on one side of the vessel)

Length (ft)	Nominal depth (ft)	Area (ft^2)
45	2.3	10.8

Additional seakeeping analyses were performed for the vessel with the bilge keel reduced in half. In the half-length bilge keel model, the front half portion of the bilge keel was removed off the full-length model as sketched on Figure 8, which potentially is in risk of interfering with the roll stabilizers and reducing stabilizer performance (References 8). These interference effects have not been fully verified, but the seakeeping results with the half-length bilge keel are included in Appendix C to indicate its potential impact on seakeeping performance of the vessel if the bilge keel needs to be downsized.

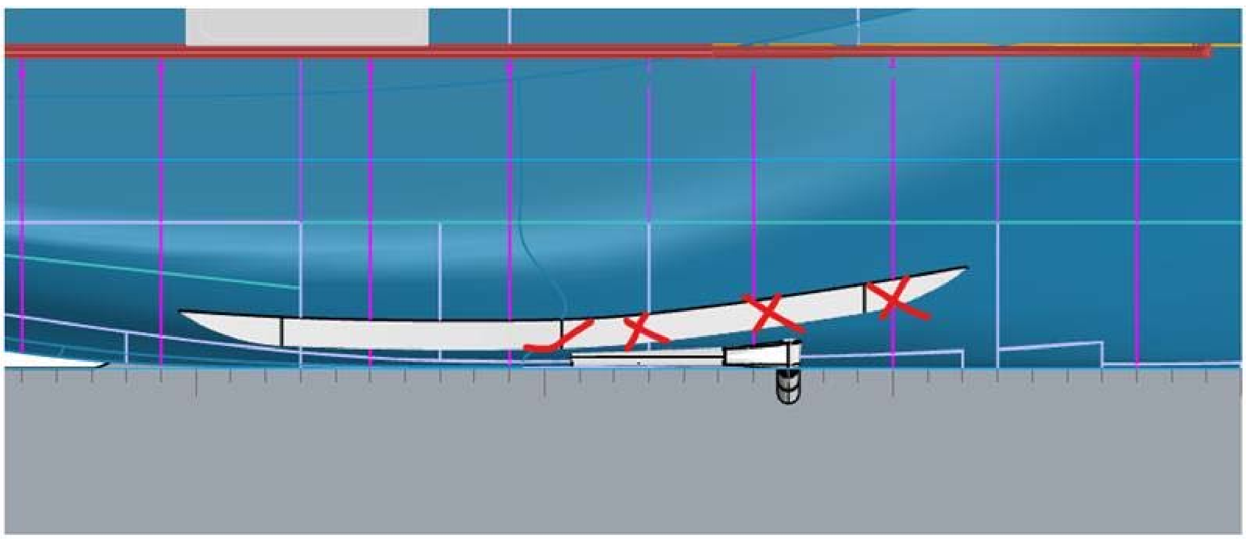


Figure 8 Conceptual sketch of the front half removal from the full bilge keel (red crosses are representing sections along the bilge keel removed for 50% bilge keel model)

Figure 9 shows the vessel roll displacements (in polar diagrams) for the vessel variants, with the full-length or half-length bilge keels on. The heave and pitch motions are not affected much by the bilge keel dimension in its current location on the hull.

The estimated amplification in RMS roll displacement at beam seas (at the worst wave headings: 105 degree or 240 degree) is approximately 25% in Sea State 4 or 5. In Sea State 3, the RMS roll displacements are all below the design criterion (3 deg. in RMS roll displacement). But in Sea States 4 and 5, reducing the bilge keel length in half will impact the operability of the vessel in terms of the maximum wave heading under which this roll motion criterion is met.

Figure 10 shows the vertical displacements (in polar diagrams) at ROV Launch Sheave for the vessel variants, with the full-length or half-length bilge keels on. Figure 11 shows the vertical displacements (in polar diagrams) at Main Crane tip for the vessel variants, with the full-length or half-length bilge keels on.

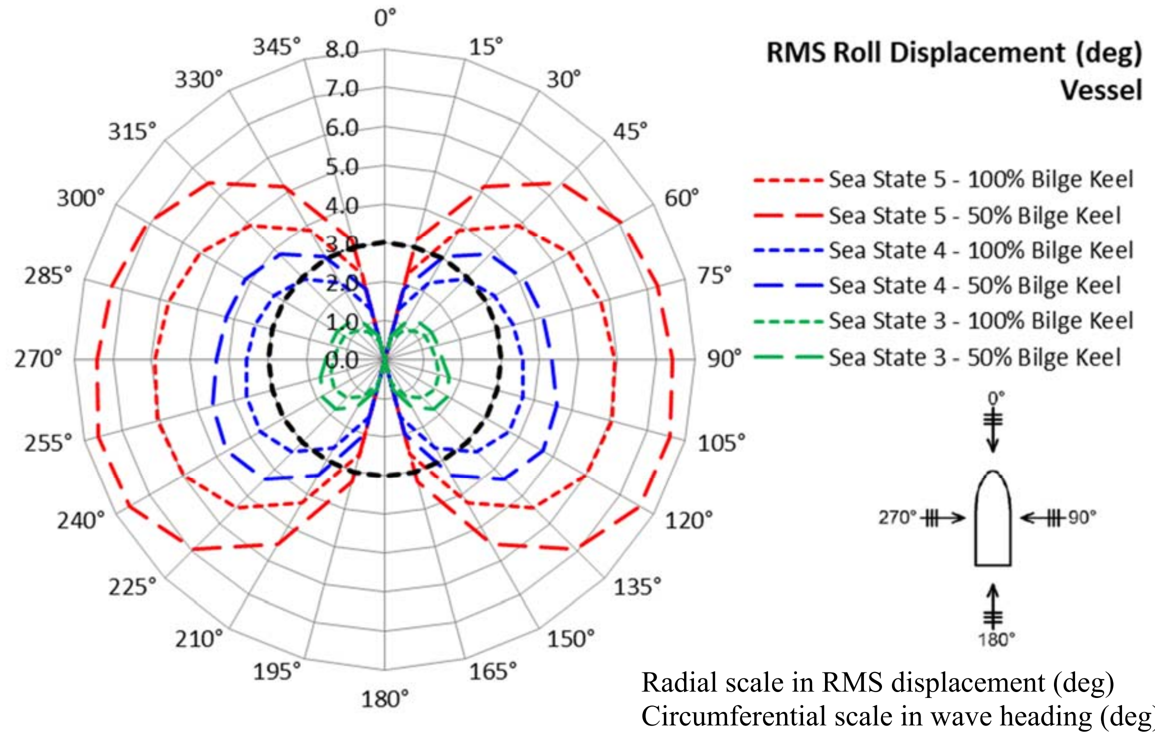


Figure 9 RMS roll displacement at vessel in Sea States 3 through 5 <u>without the active roll stabilizers operating</u> – full-length (100%) versus half-length (50%) bilge keels

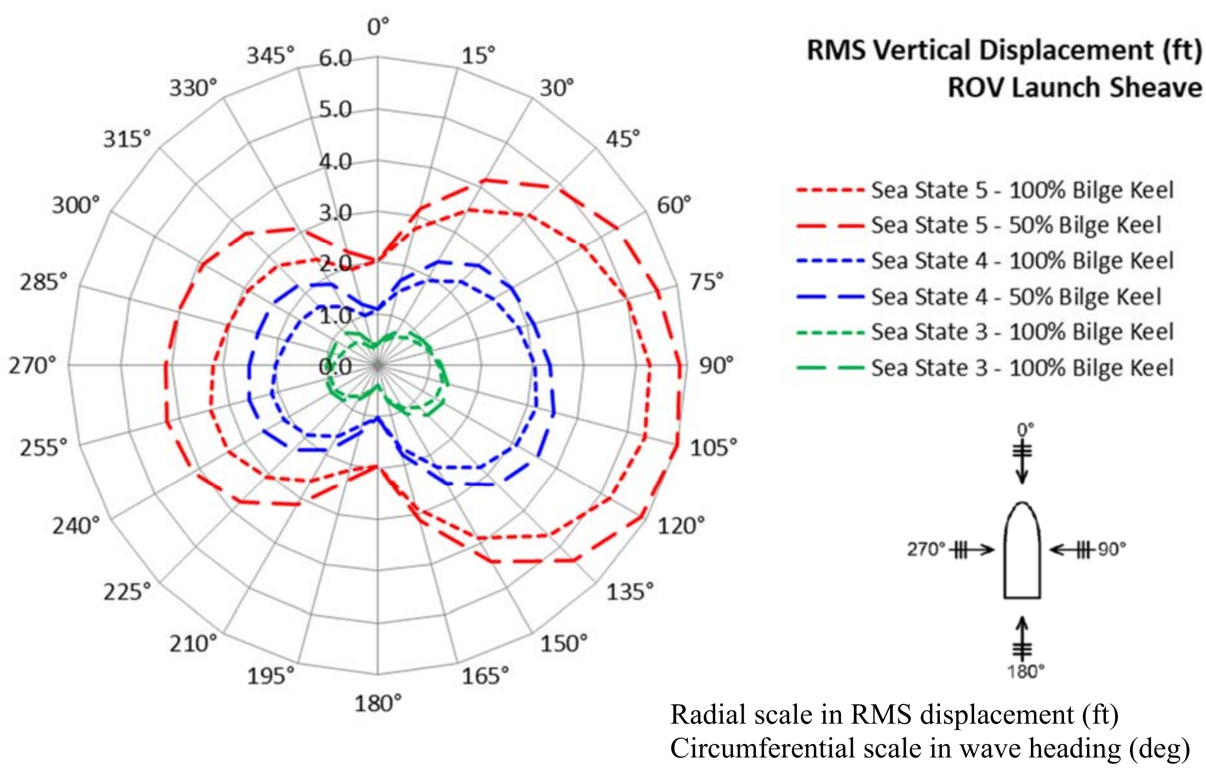


Figure 10 RMS vertical displacement at ROV Launch Sheave in Sea States 3 through 5 <u>without the active roll stabilizers operating</u> – full-length (100%) versus half-length (50%) bilge keels

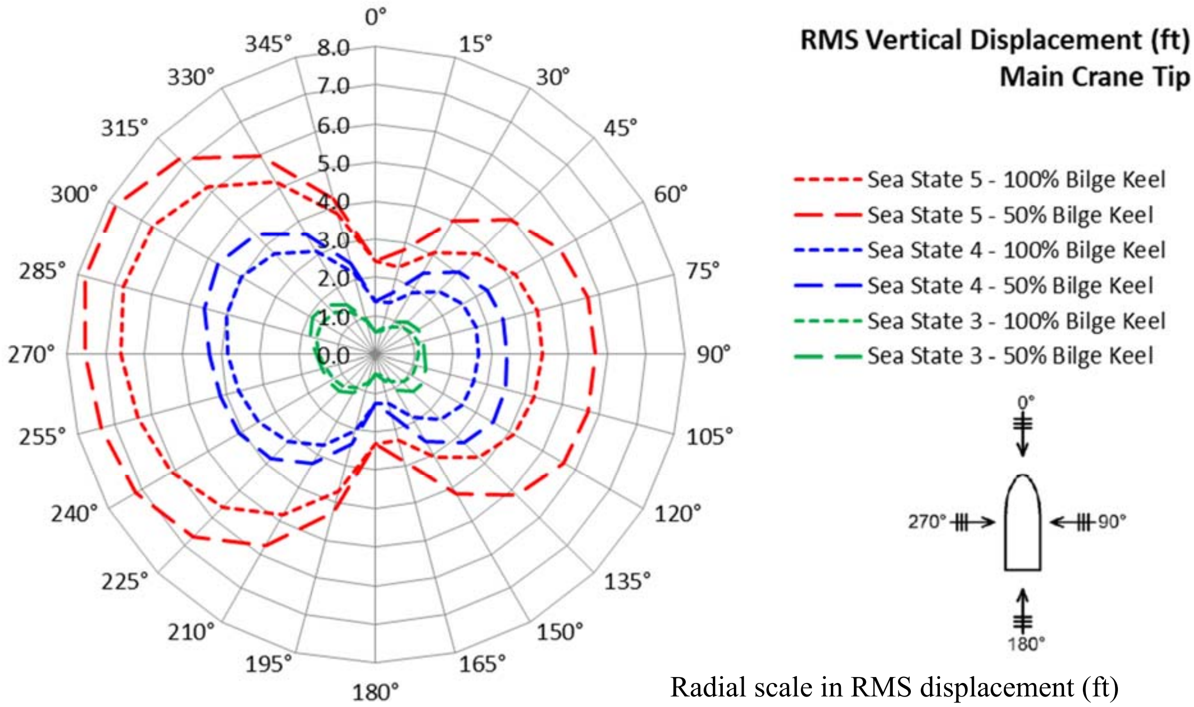


Figure 11 RMS vertical displacement at Main Crane tip in Sea States 3 through 5 without the active roll stabilizers operating – full-length (100%) versus half-length (50%) bilge keels

Seakeeping Results

Results Presentation Format

It should be noted that the vessel responses reported are RMS values, not extreme values. This allows a direct comparison against the seakeeping performance requirements (Reference 13) defined in terms of RMS motions or RMS accelerations at ship and specific points of interest.

The full set of seakeeping results is included as Appendices A through D. Appendix A contains results in polar form for Sea States 3, 4, and 5 for the vessel with roll stabilizers turned on and with the full-length bilge keel on. Appendix B and Appendix C contain some of the results from the seakeeping model with roll stabilizers turned off and with the full-length or half-length bilge keels, respectively. Appendix D contains Response Amplitude Operators for the vessel with roll stabilizers turned on and with the full-length bilge keel on.

Motion Sickness Incidence

Motion Sickness Incidence (MSI) is the percentage of people that experience motion sickness over a period of time while exposed to an oscillatory environment. The method presented in Reference 15 was used in SMP to calculate MSI. The MSI calculation is based on a Motion Sickness Dose Value (MSDV) that is based on the frequency-weighted vertical acceleration a person experiences over a period of time, as shown:

$MSDV = \sqrt{\int_0^T a_w^2(t)dt}$ where

$a_w(t)$ is the frequency-weighted vertical acceleration, and

T is the total period of time (in seconds) of exposure to the motion.

For a continuous and approximately constant magnitude motion, the formula above can be simplified:

$MSDV = \overline{a_w}\sqrt{T}$ where

$\overline{a_w}$ is the RMS frequency-weighted vertical acceleration.

The simplified expression is used to determine MSDV. The percentage of people that will experience motion sickness may be estimated by:

$MSI = K_m MSDV$ where

K_m is a constant which varies according to the exposed population.

For a mixed population of males and females that were not exposed to the motions for a long period of time (i.e., several days), K_m is equal to 1/3.

Motion Induced Interruptions

Motion Induced Interruptions (MIIs) are loss-of-balance events due to tipping or sliding. MIIs are presented as the number of loss-of-balance events per unit of time, typically one minute.

The method presented in Reference 14 was used in SMP to calculate MII. For the purposes of simplicity, MIIs due to sliding are ignored. Sliding can be an important contributor when working outside on a wet deck. The places of interest are interior spaces, however, so only tipping was considered.

The tipping calculation assumes that a person may be approximated by a rigid ellipsoidal cylinder, with a “strong” axis and a “weak” axis, represented by the major and minor axes of the cylinder. Tipping is assumed to be a combination of lateral, longitudinal, and vertical motions.

Two important ratios involved in the calculation of MII are the lateral tipping coefficient, l/h, and the longitudinal tipping coefficient, d/h. The lateral tipping coefficient is the ratio between a person’s half stance and the height of the center of gravity, as shown in Figure 12. Similarly, the longitudinal tipping coefficient contains the quantity d, which is half the distance between the toes and the heel. According to Reference 14, l/h can be assumed to be 0.25 and d/h can be assumed to be 0.17.

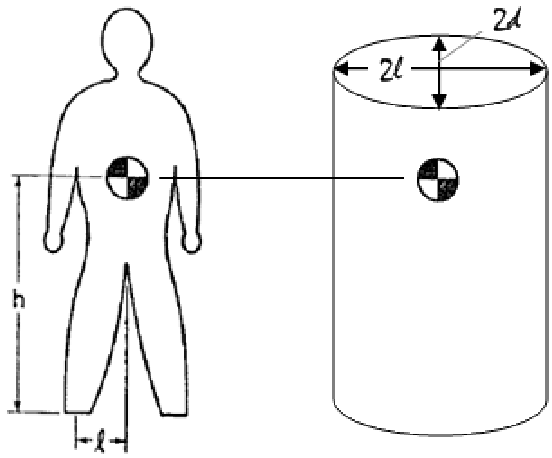


Figure 12 Model of a person on deck which shows the tipping coefficient components

The tipping process is further simplified by assuming that a person can only tip forward, backward, and side-to-side. Although in reality a person can tip to any arbitrary direction, for the purposes of this analysis, forward/back and side/side tipping were considered to model the process adequately.

A person can be facing any direction relative to the vessel. MIIs were calculated for a person facing forward, facing to port, and facing to the port bow (45 deg from forward). The reported MIIs are for the person's heading that maximized the number of interruptions.

Vessel Motions

Polar Diagrams

Heave, roll and pitch displacement at the vessel with the active roll stabilizers operating are shown in Figure 13 through Figure 15. Only the displacement polar diagrams are shown for discussion because similar trends are present in the velocity and acceleration (Appendix A).

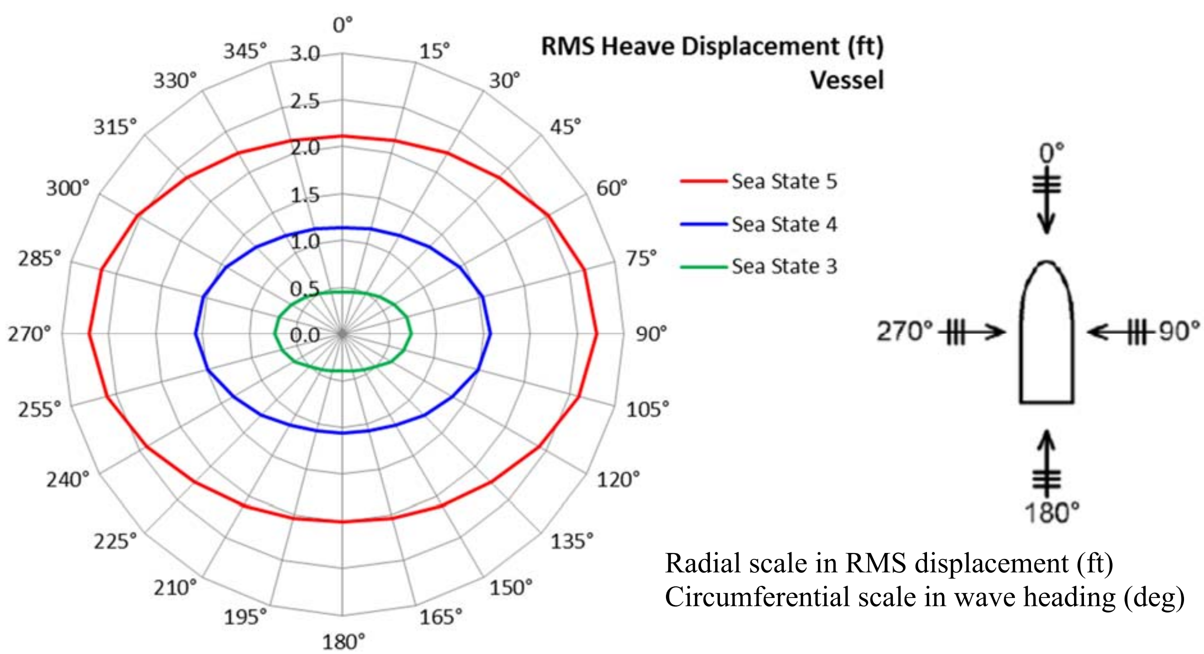


Figure 13 RMS heave displacement at vessel in Sea States 3 through 5

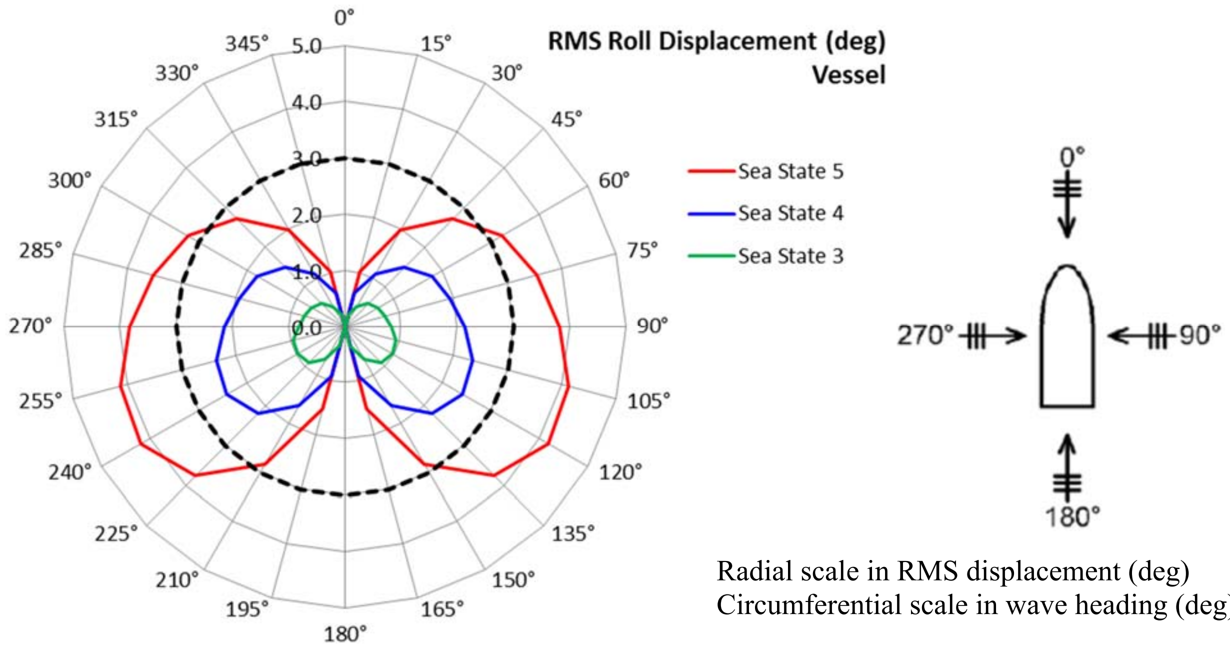


Figure 14 RMS roll displacement at vessel in Sea States 3 through 5

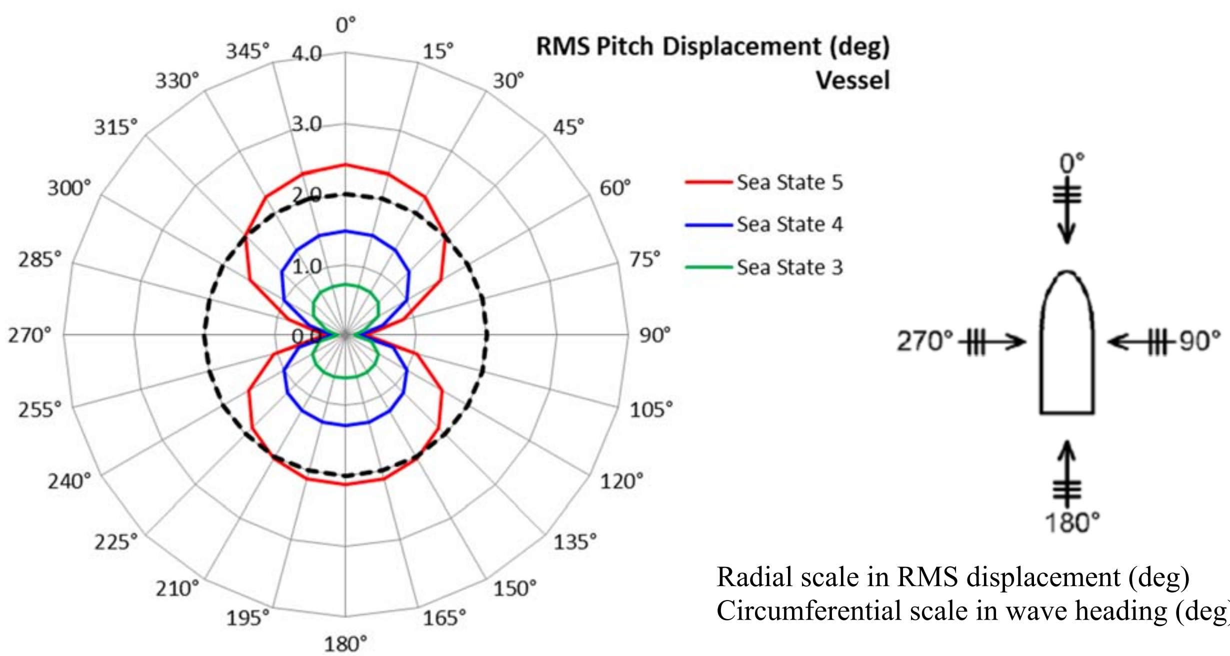


Figure 15 RMS pitch displacement at vessel in Sea States 3 through 5

Motions at ROV Launch Sheave

Polar Diagrams

Lateral and vertical displacement at the ROV Launch Sheave for the vessel variants are shown in Figure 16 and Figure 17. Only the displacement polar diagrams are shown for discussion because similar trends are present in the lateral and vertical velocity and acceleration (Appendix A).

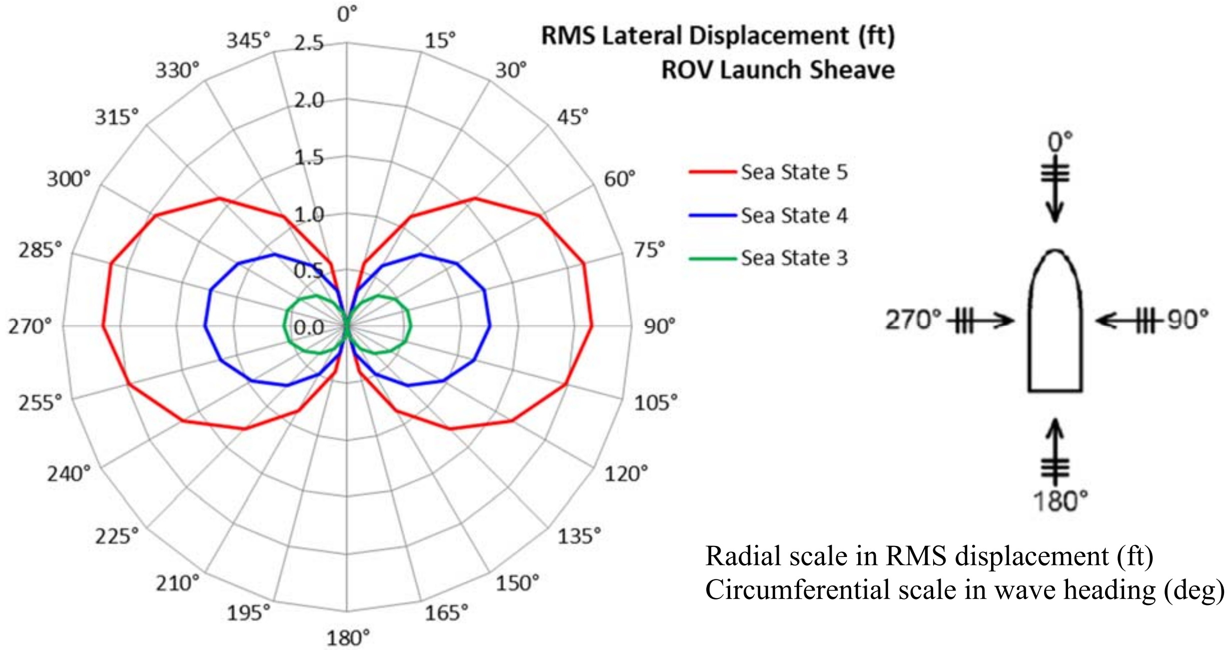


Figure 16 RMS lateral displacement at ROV Launch Sheave in Sea States 3 through 5

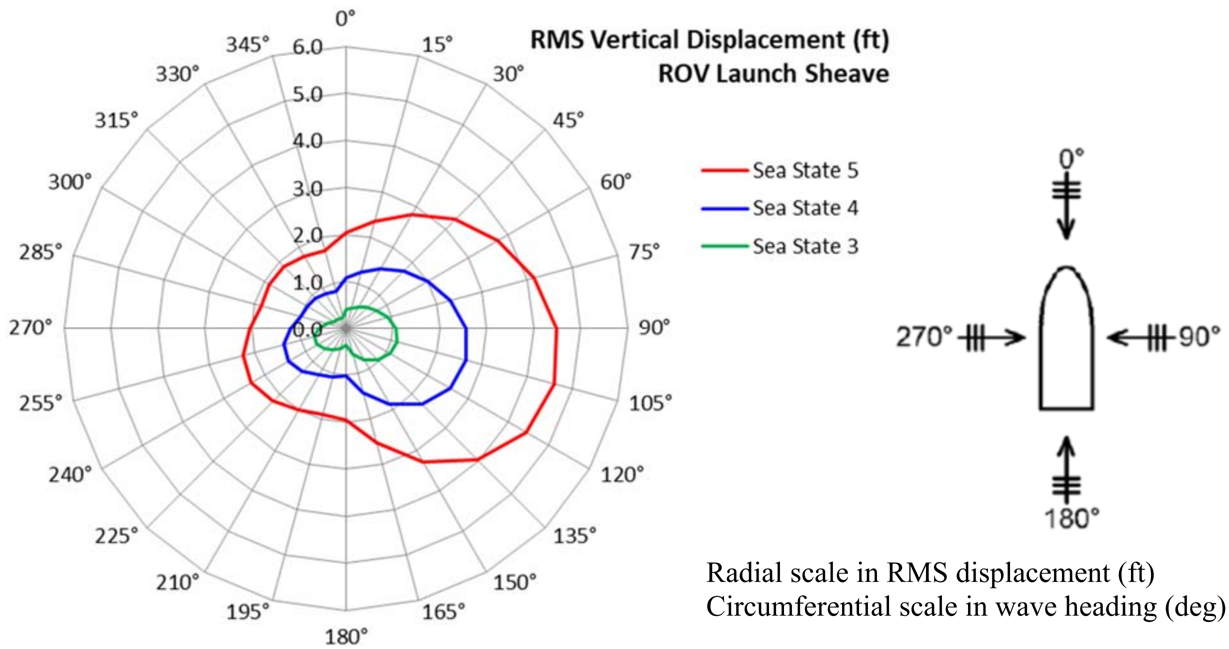


Figure 17 RMS vertical displacement at ROV Launch Sheave in Sea States 3 through 5

Motions at Stern A-Frame Sheave

Polar Diagrams

Lateral and vertical displacement at the Stern A-Frame Sheave for the vessel variants are shown in Figure 18 and Figure 19. Only the displacement polar diagrams are shown for discussion because similar trends are present in the lateral and vertical velocity and acceleration (Appendix A).

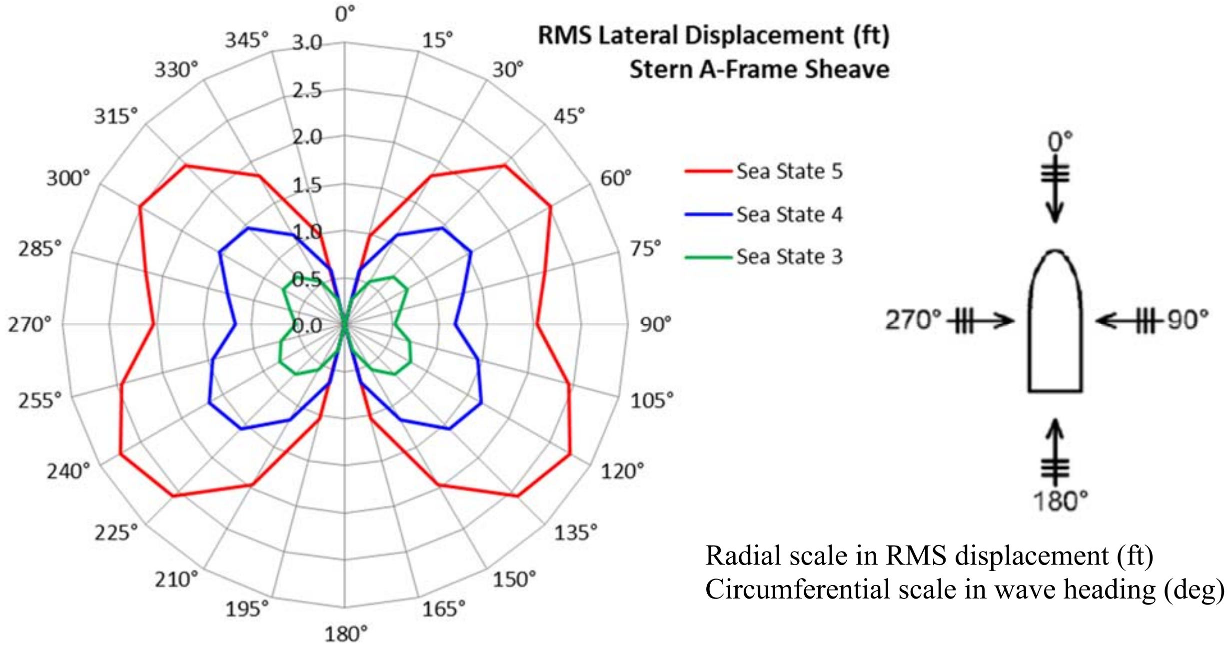


Figure 18 RMS lateral displacement at Stern A-Frame Sheave in Sea States 3 through 5

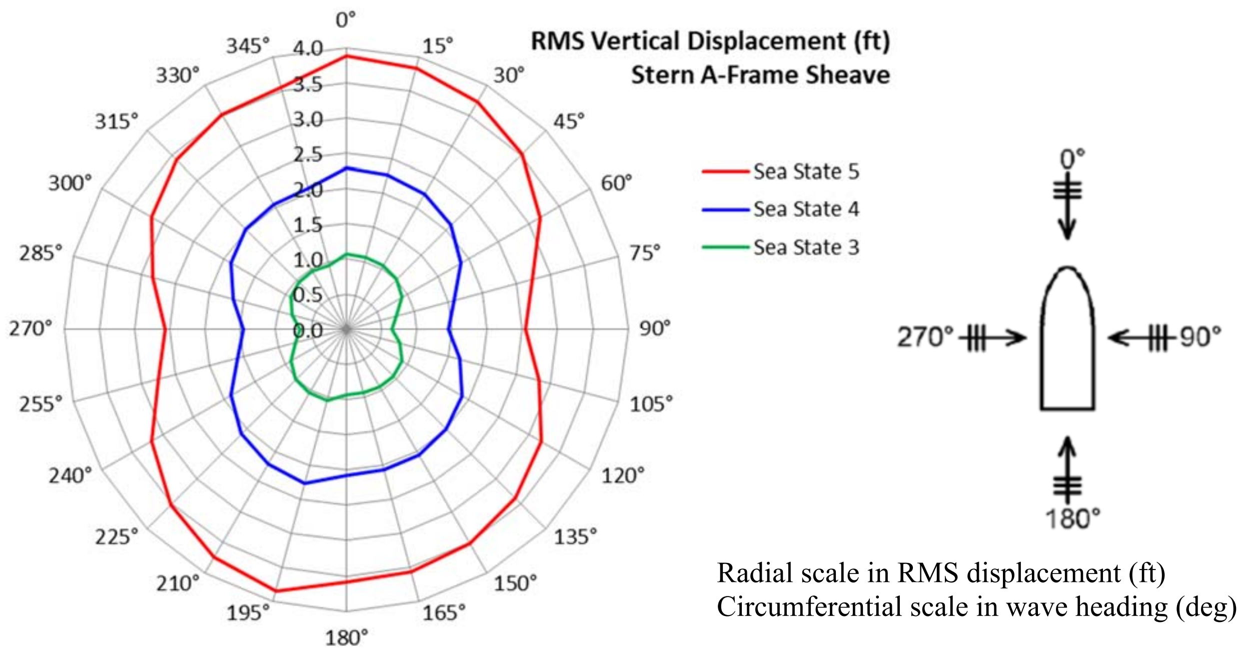


Figure 19 RMS vertical displacement at Stern A-Frame Sheave in Sea States 3 through 5

Motions at Main Crane Tip

Polar Diagrams

Lateral and vertical displacement at the Main Crane tip for the vessel variants are shown in Figure 20 and Figure 21. Only the displacement polar diagrams are shown for discussion because similar trends are present in the lateral and vertical velocity and acceleration (Appendix A).

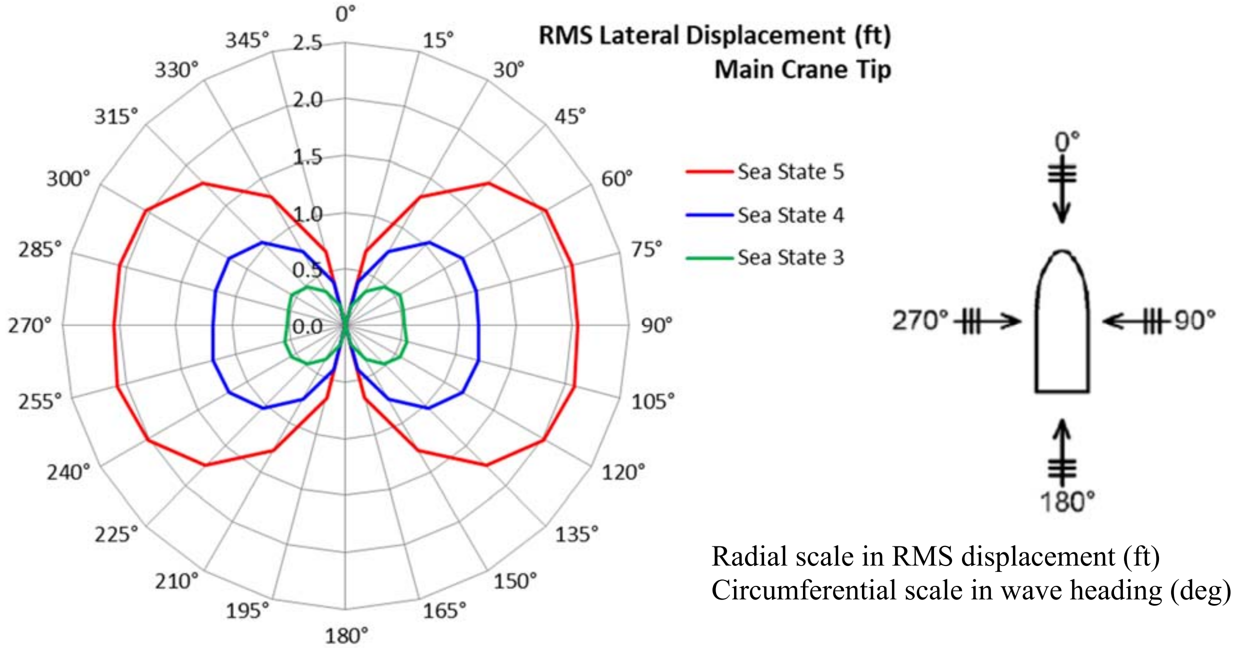


Figure 20 RMS lateral displacement at Main Crane tip in Sea States 3 through 5

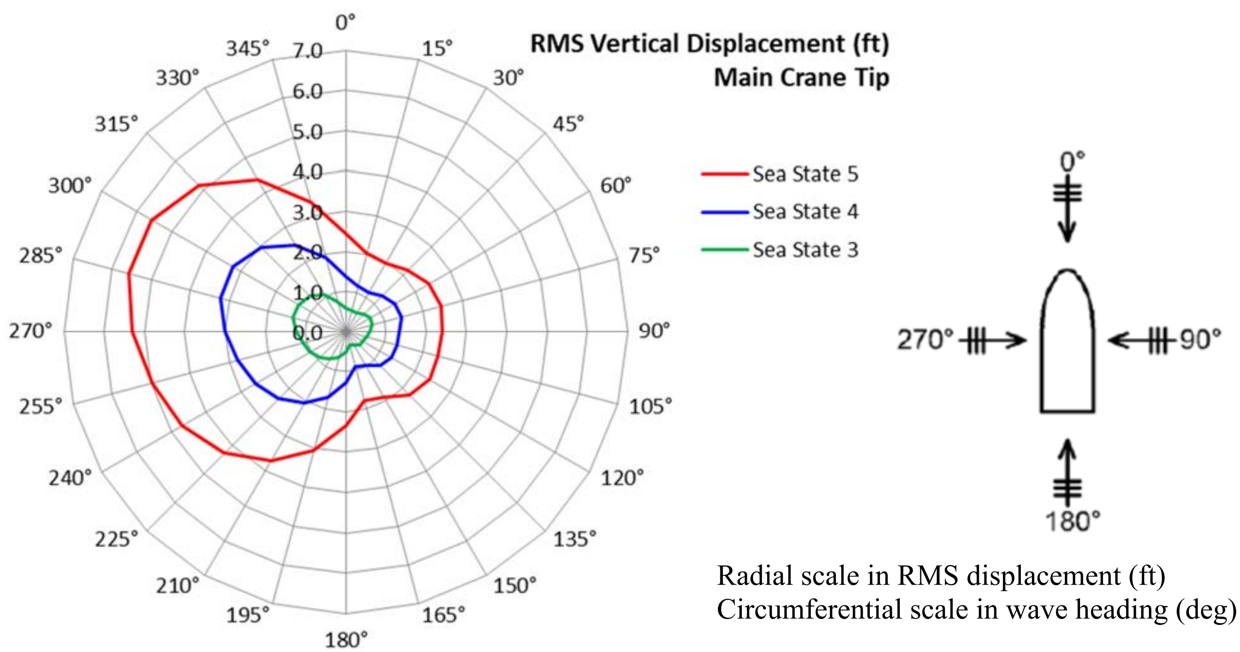


Figure 21 RMS vertical displacement at Main Crane tip in Sea States 3 through 5

Motions at Middle of Pilothouse

Polar Diagrams

Lateral and vertical displacement at the middle of Pilothouse for the vessel variants are shown in Figure 22 and Figure 23. Only the displacement polar diagrams are shown for discussion because similar trends are present in the lateral and vertical velocity and acceleration (Appendix A).

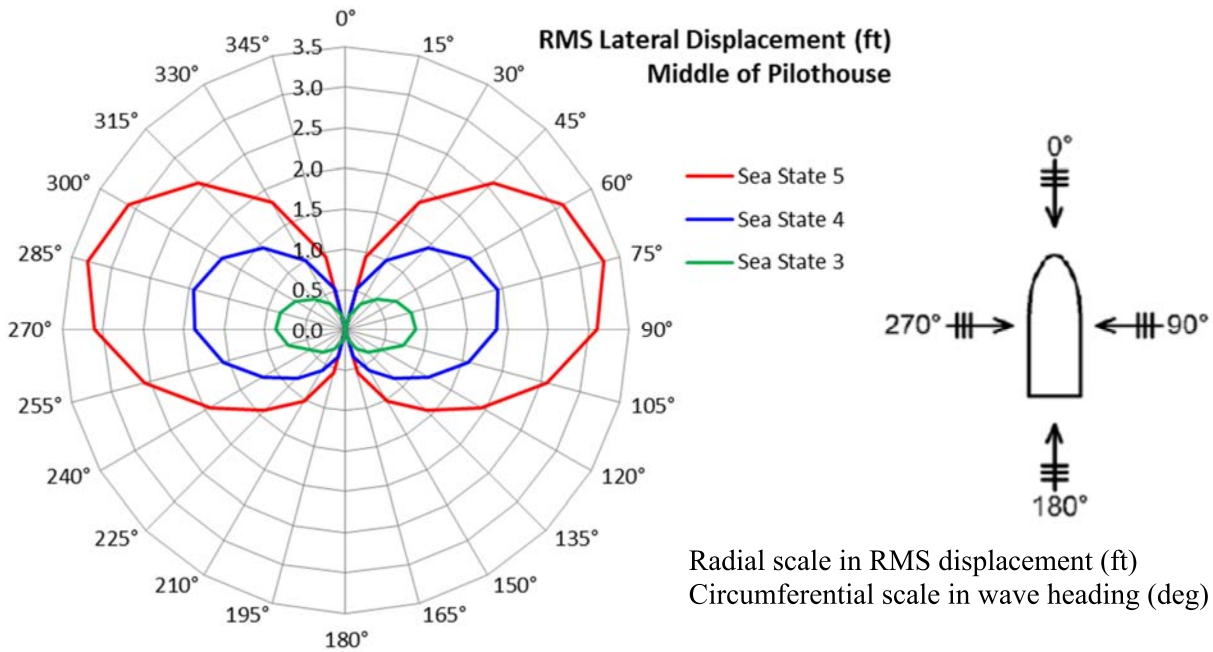


Figure 22 RMS lateral displacement at middle of Pilothouse in Sea States 3 through 5

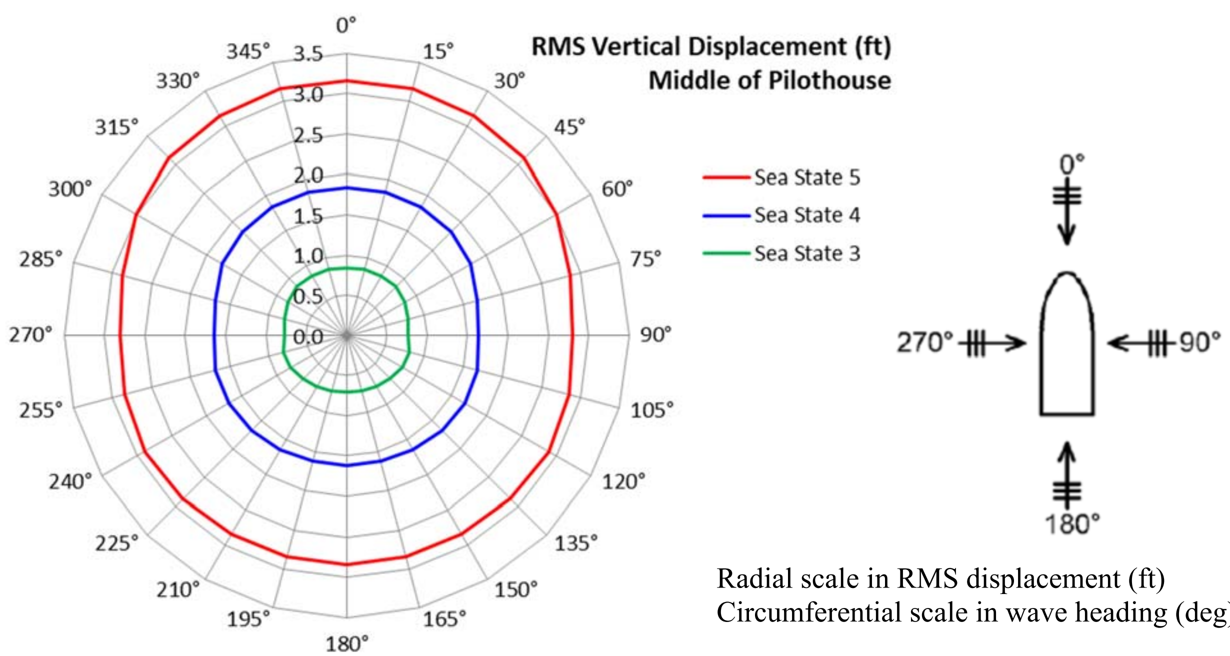


Figure 23 RMS vertical displacement at middle of Pilothouse in Sea States 3 through 5

Motions at Middle of Wet Lab

Polar Diagrams

Lateral and vertical displacement at the middle of Wet Lab for the vessel variants are shown in Figure 24 and Figure 25. Only the displacement polar diagrams are shown for discussion because similar trends are present in the lateral and vertical velocity and acceleration (Appendix A).

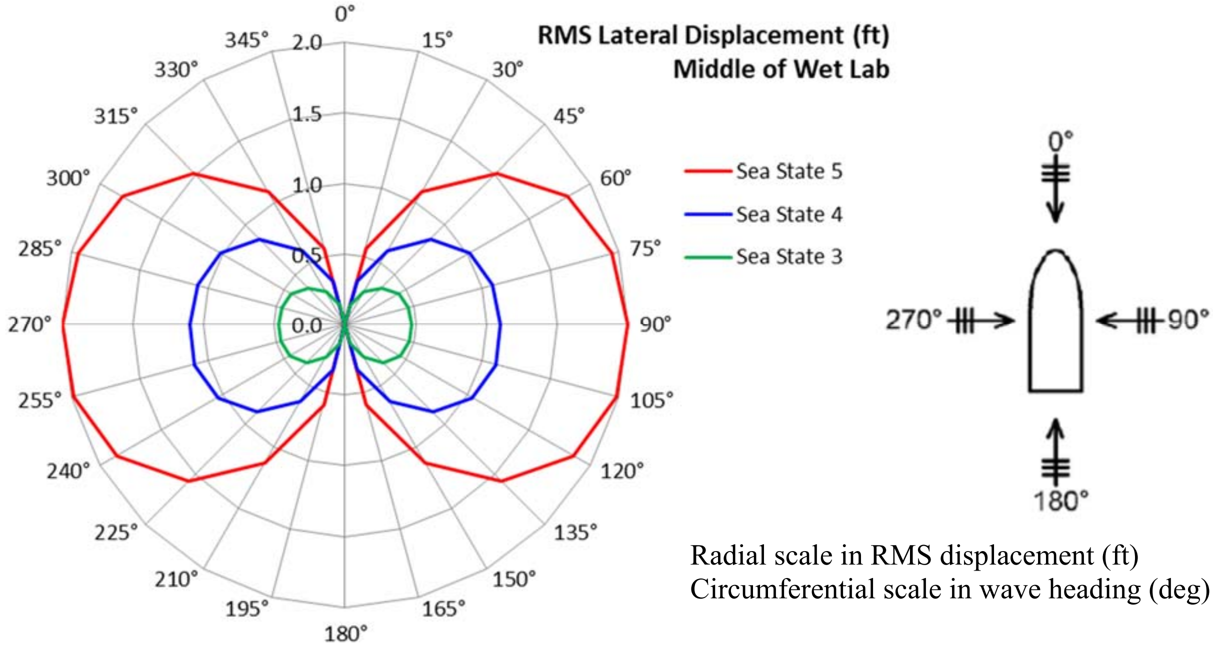


Figure 24 RMS lateral displacement at middle of Wet Lab in Sea States 3 through 5

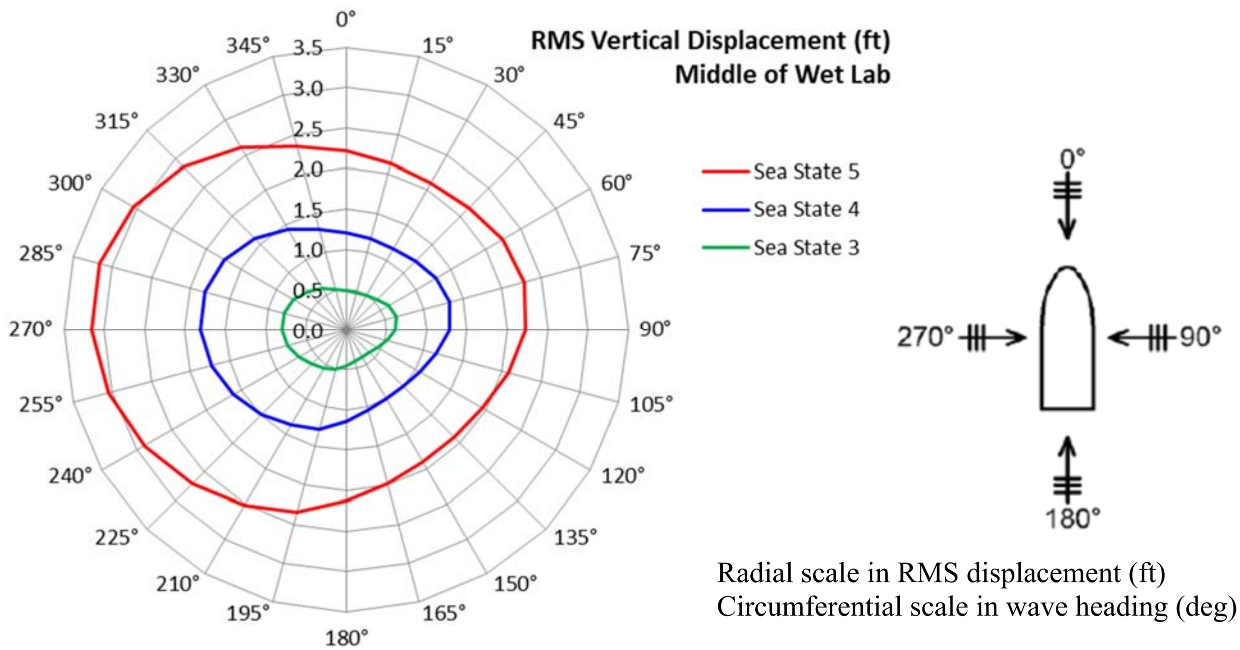


Figure 25 RMS vertical displacement at middle of Wet Lab in Sea States 3 through 5

Motions at Middle of Control Room

Polar Diagrams

Lateral and vertical displacement at the middle of Control Room for the vessel variants are shown in Figure 26 and Figure 27. Only the displacement polar diagrams are shown for discussion because similar trends are present in the lateral and vertical velocity and acceleration (Appendix A).

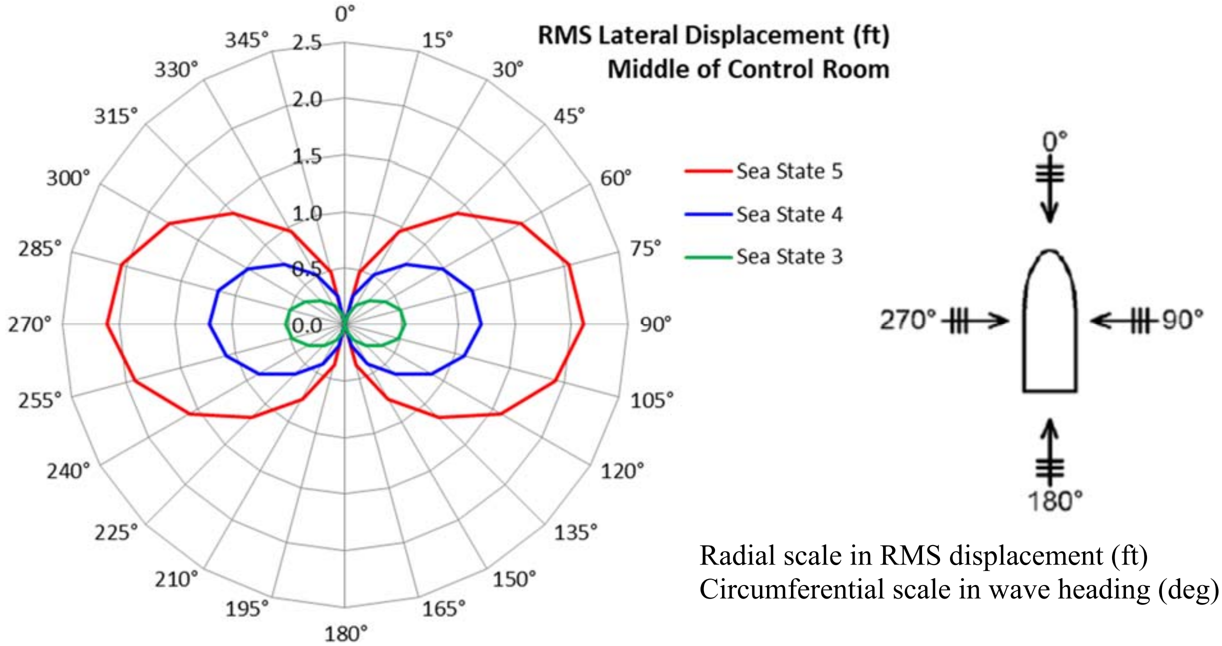


Figure 26 RMS lateral displacement at middle of Control Room in Sea States 3 through 5

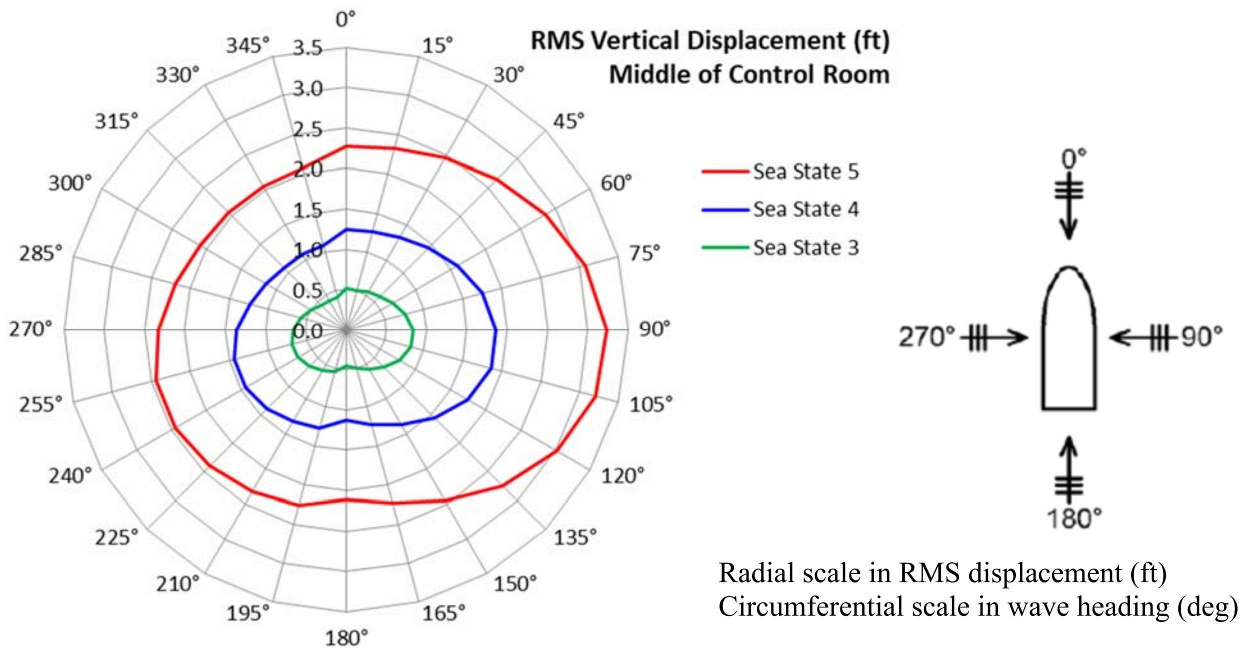


Figure 27 RMS vertical displacement at middle of Control Room in Sea States 3 through 5

Motions at Main Deck Amidship at Deck Edge

Polar Diagrams

Lateral and vertical displacement at the Main Deck amidship at deck edge for the vessel variants are shown in Figure 28 and Figure 29. Only the acceleration polar diagrams are shown for discussion. See Appendix A for the lateral and vertical displacement and velocity.

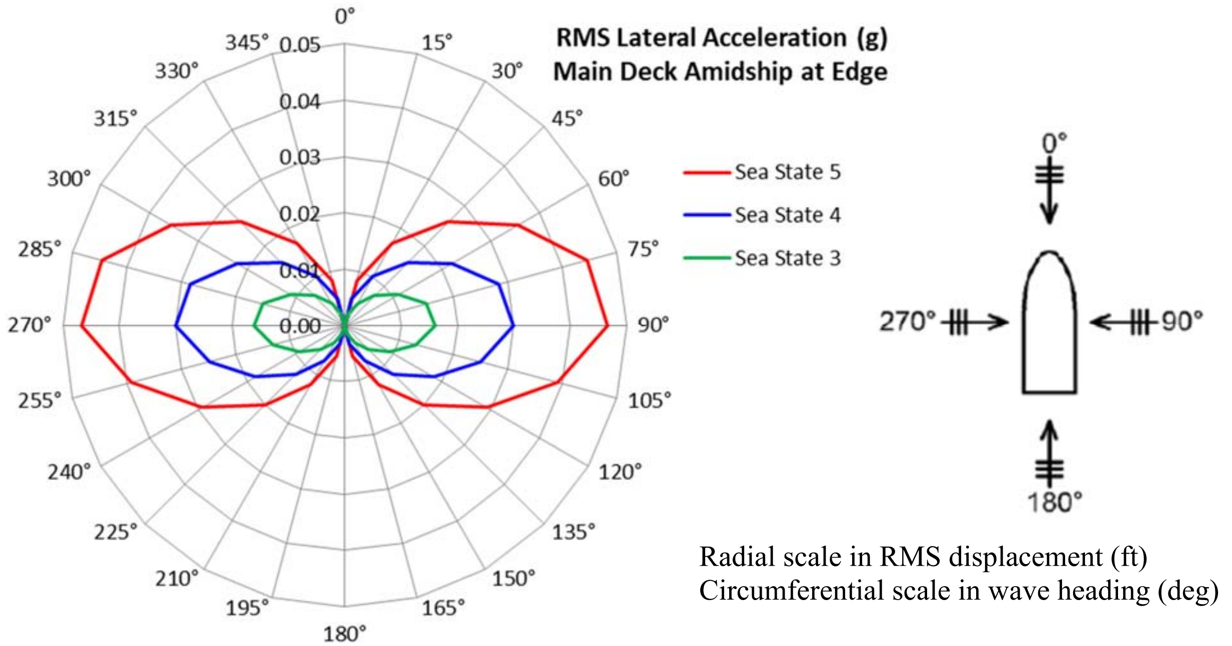


Figure 28 RMS lateral acceleration at Main Deck amidship at deck edge in Sea States 3 through 5

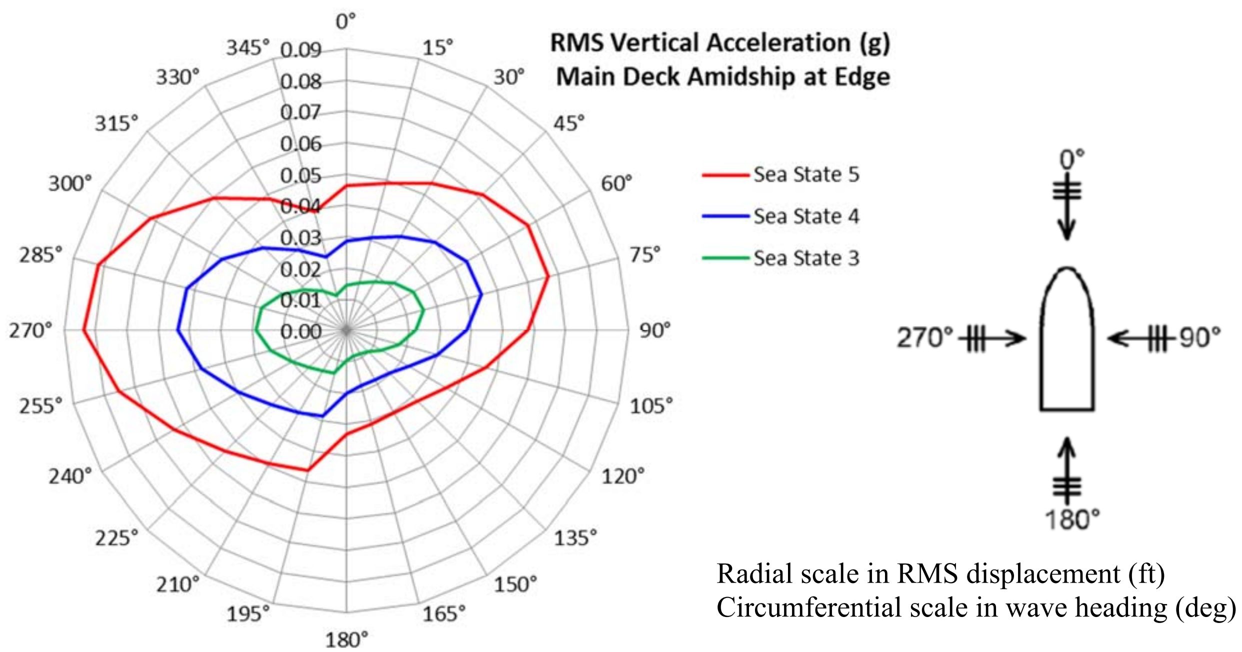


Figure 29 RMS vertical acceleration at Main Deck amidship at deck edge in Sea States 3 through 5

Human Factors (MSI & MII)

Polar Diagrams

Seasickness and the ability to stay standing upright are human factors that can be quantified by Motion Sickness Incidence (MSI) and Motion Induced Interruptions (MII), respectively. MII, in particular, is not a linear function of significant wave height, so the results in several sea states can be quite different.

MSI for a person in the Control Room is shown in Figure 30. MSI is a function of vertical acceleration only.

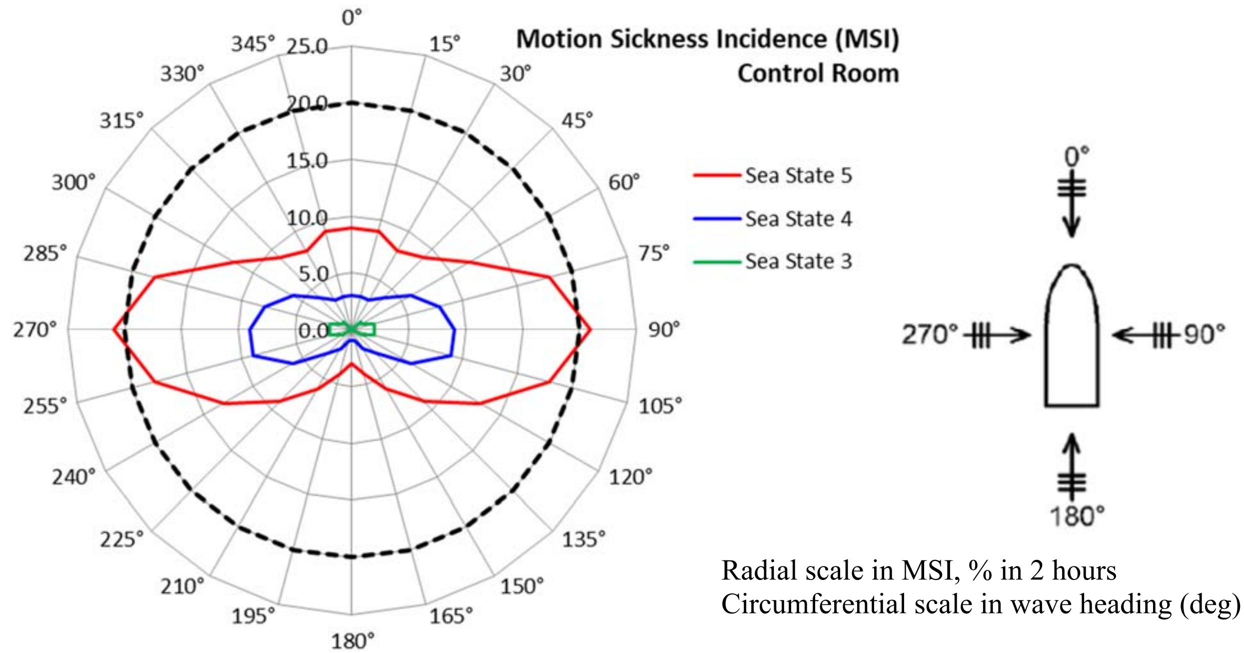


Figure 30 MSI in the Control Room in Sea States 3 through 5

A nominal 20% MSI in 2 hours is shown on the polar diagram. This is not a specified criterion, but it is a commonly cited limit for working on a seagoing vessel.

MII for a person in the Control Room is shown in Figure 31. MII is a function of vertical, lateral, and longitudinal acceleration. The MSI and MII for the Pilothouse and Wet Lab are reported at Appendix A.

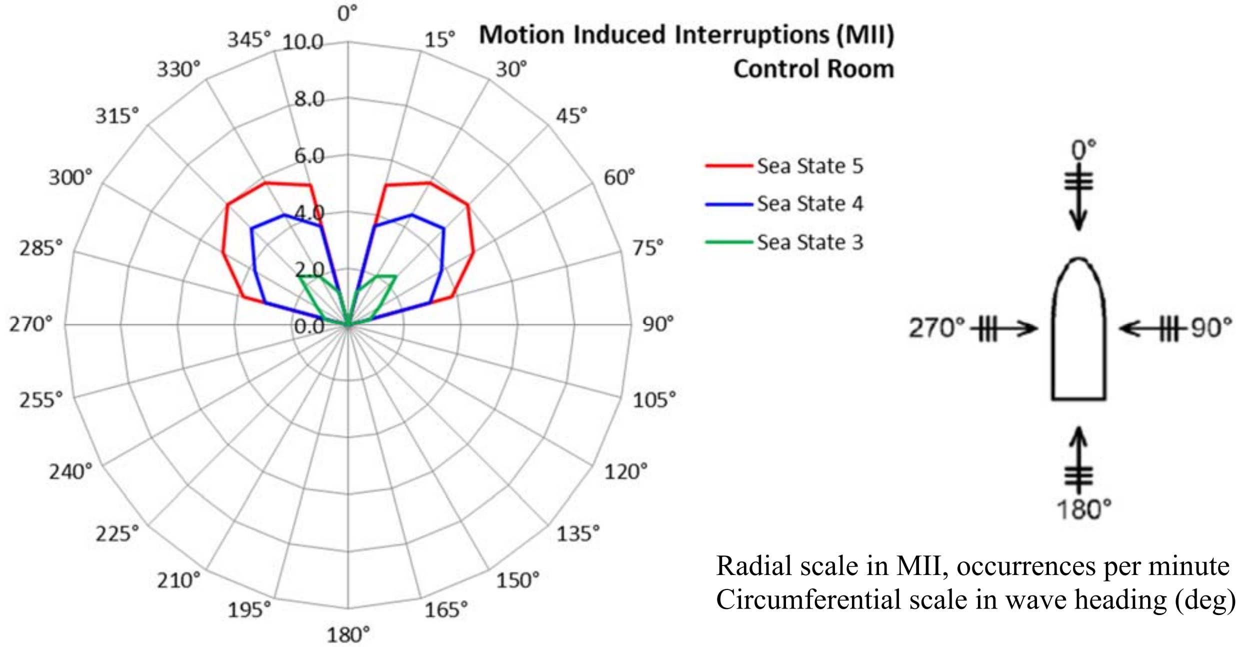
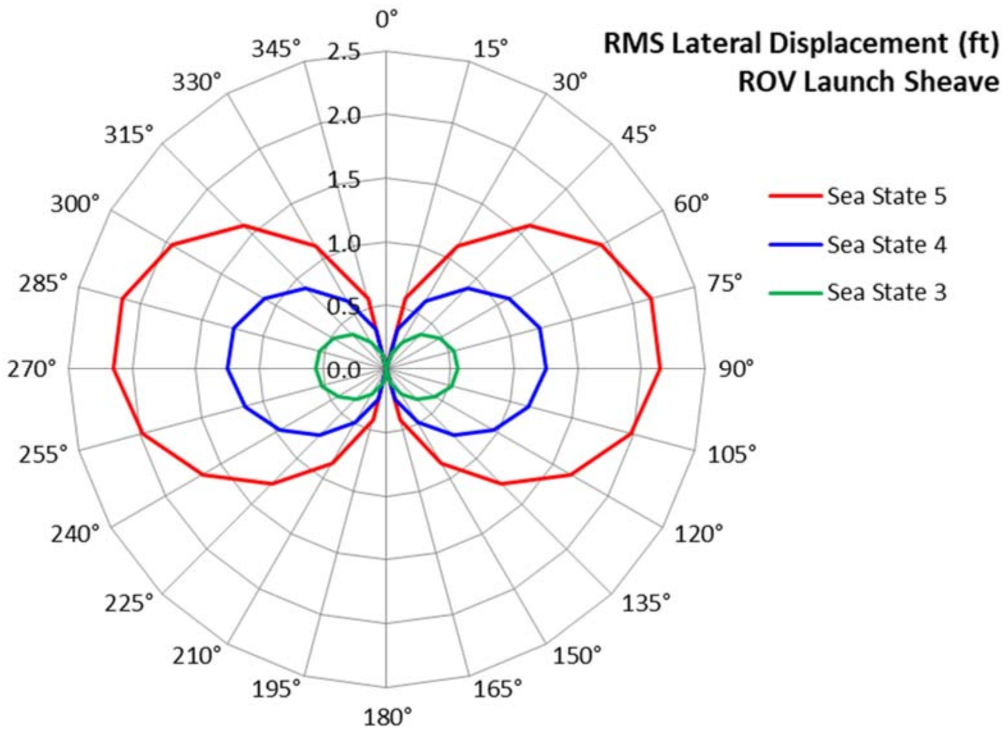


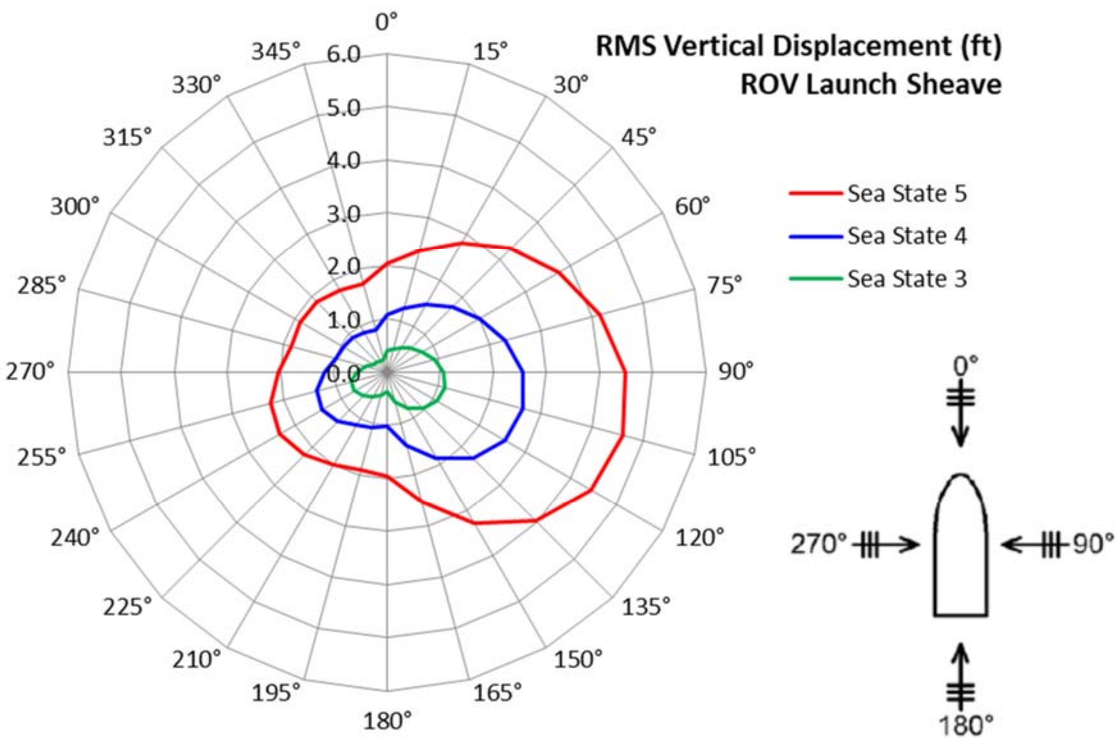
Figure 31 MII in the Control Room in Sea States 3 through 5

Appendix A Polar Diagrams – Vessel with Roll Stabilizers Turned On and with Full-Length Bilge Keel

RMS Displacements at ROV Launch Sheave

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

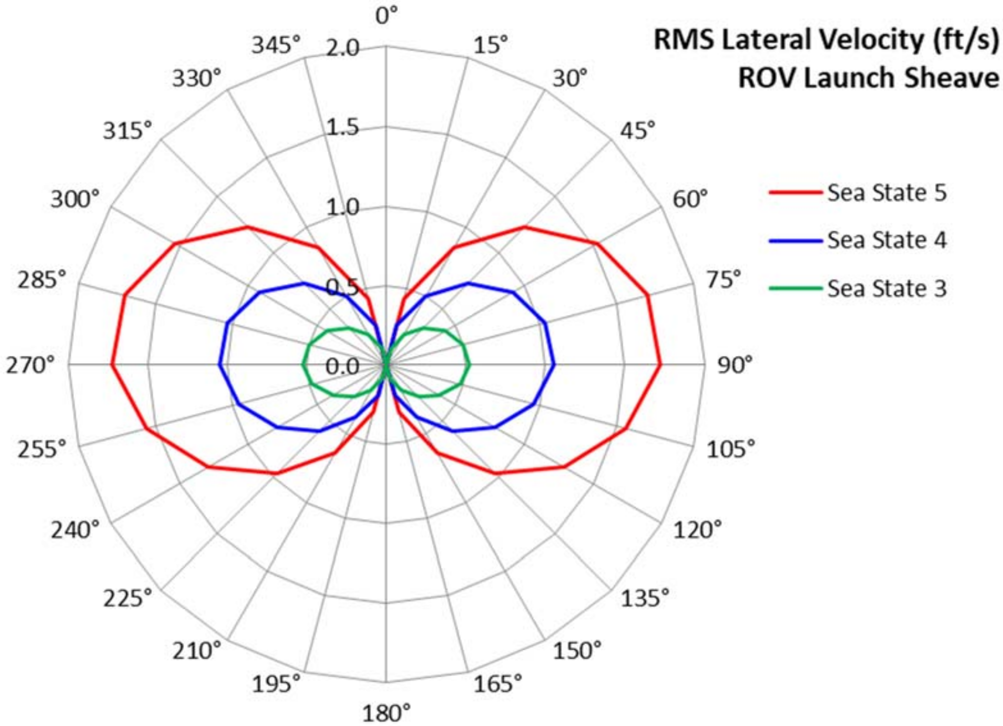


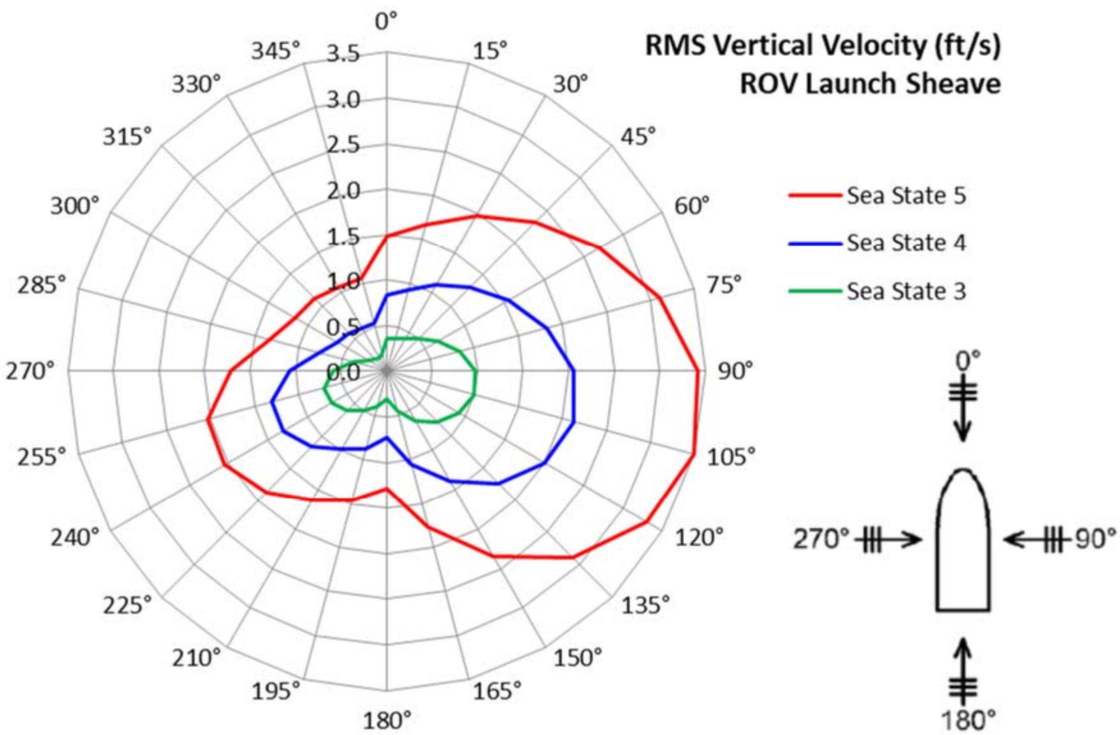


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at ROV Launch Sheave

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

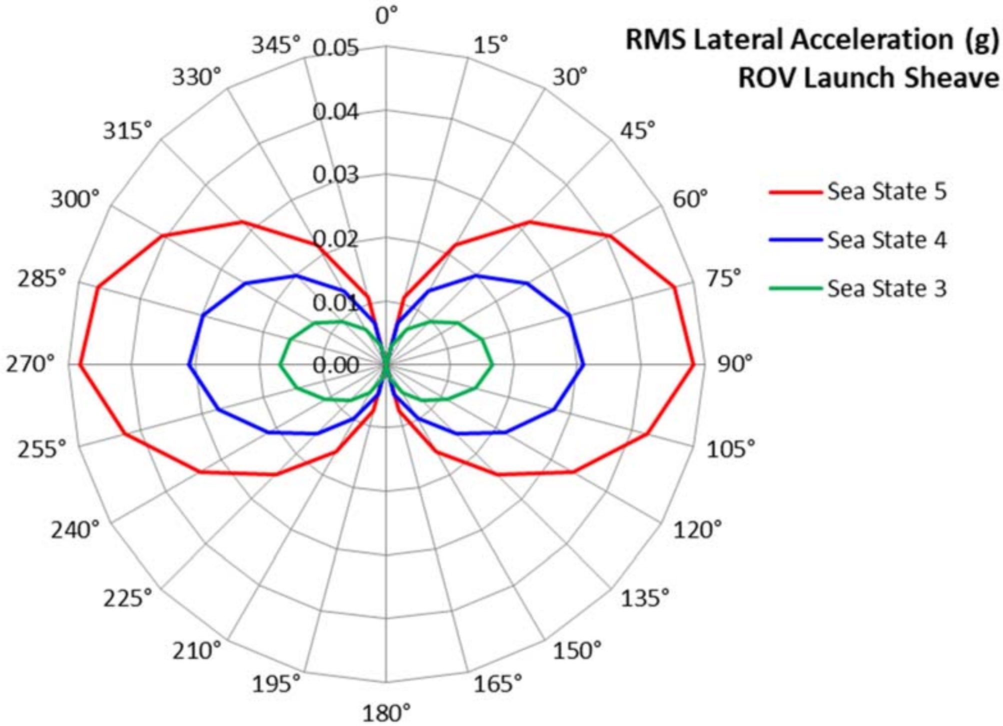


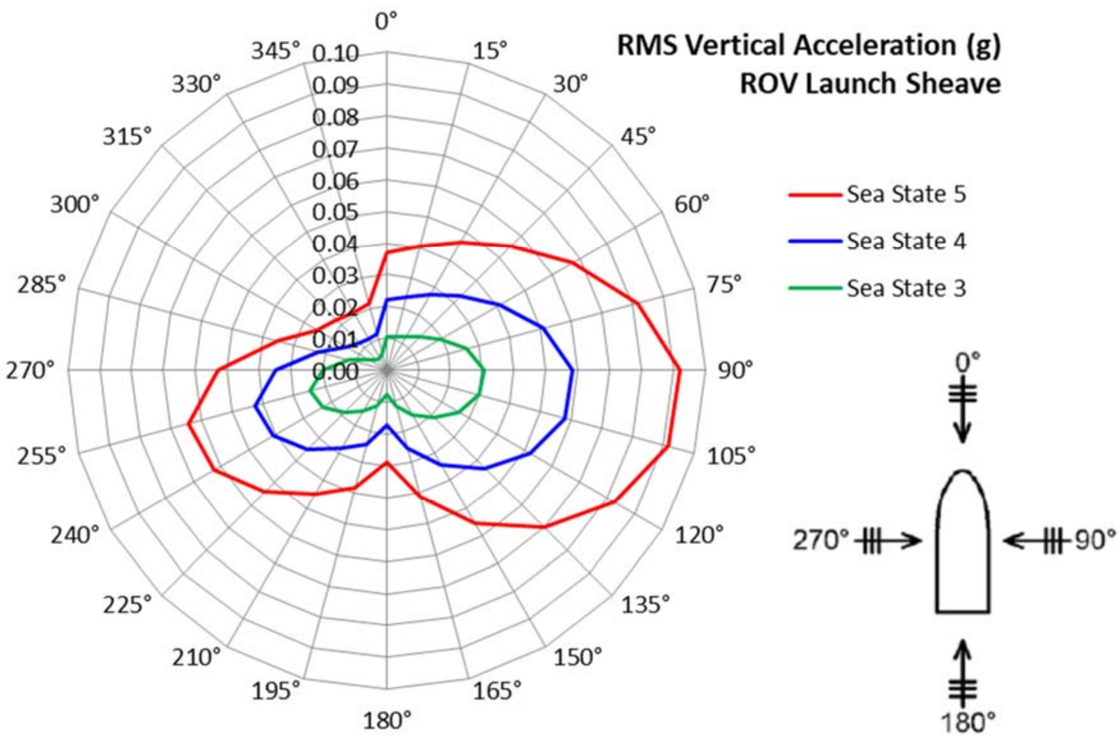


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at ROV Launch Sheave

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

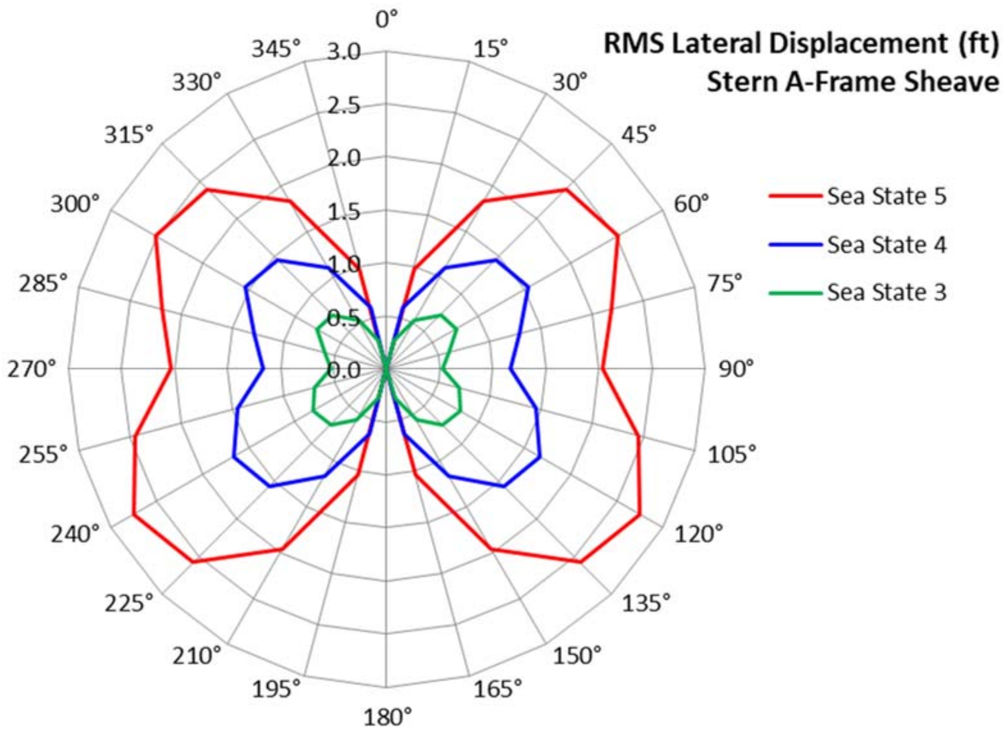


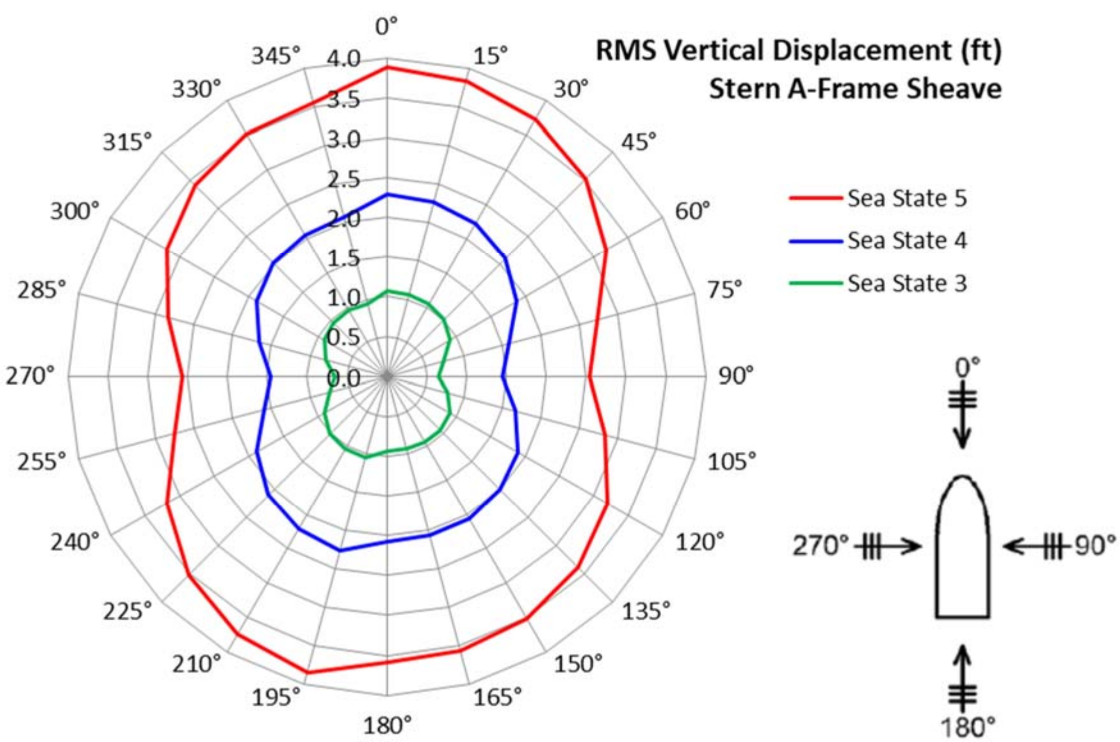


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Stern A-Frame Sheave

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

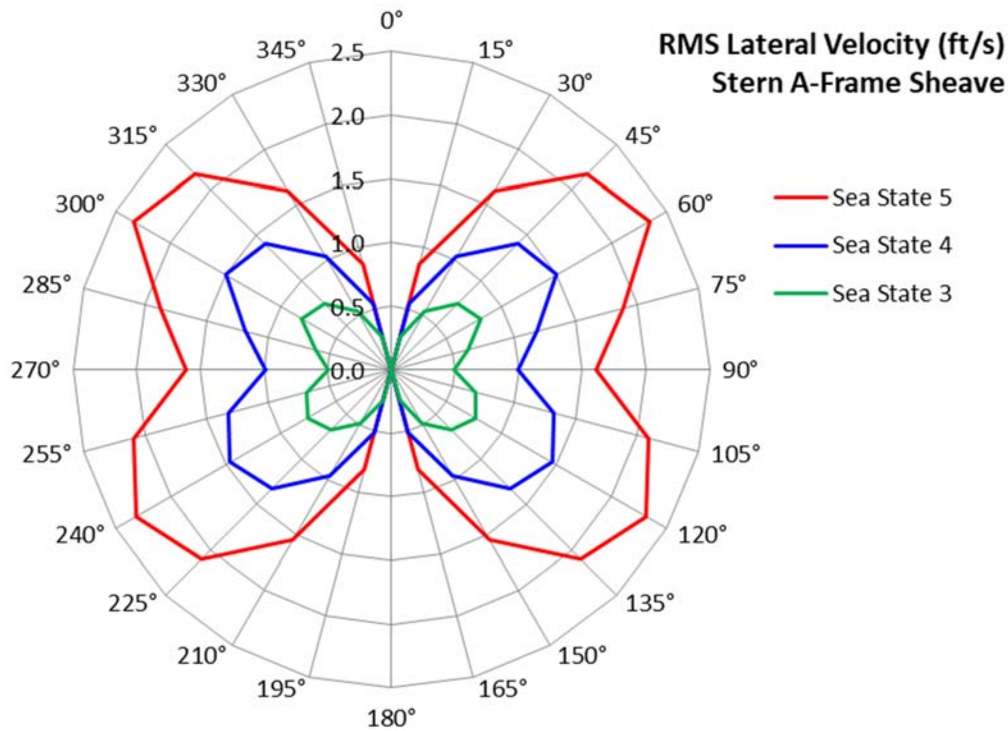


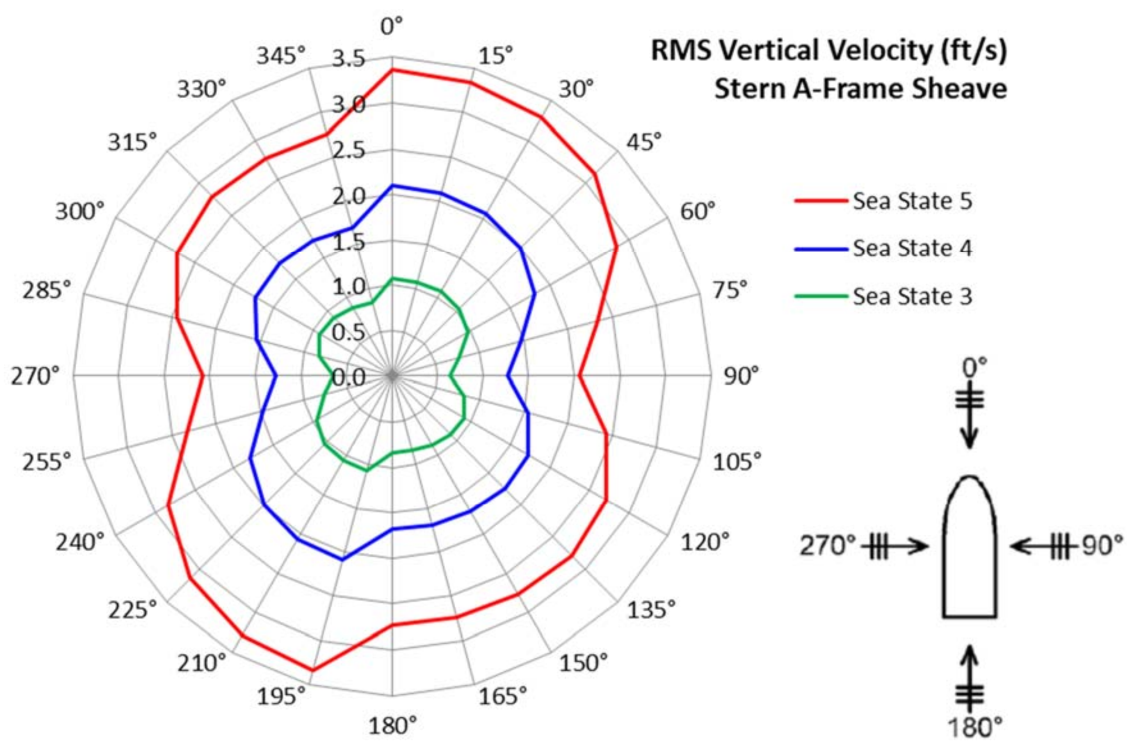


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Stern A-Frame Sheave

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

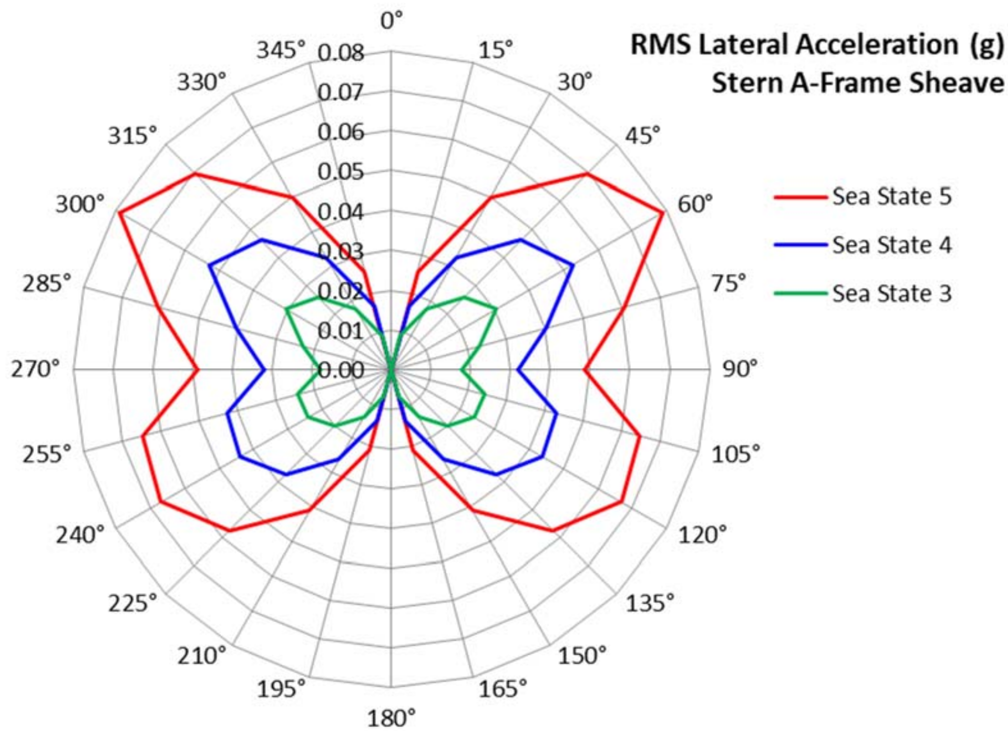


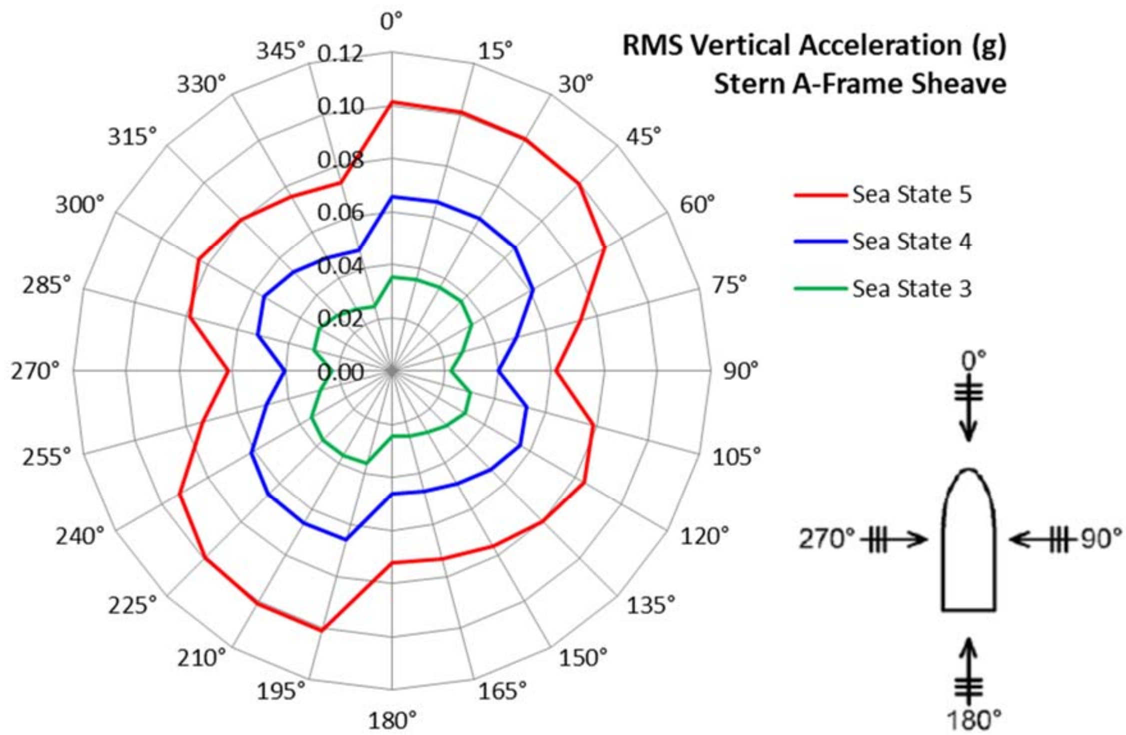


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Stern A-Frame Sheave

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

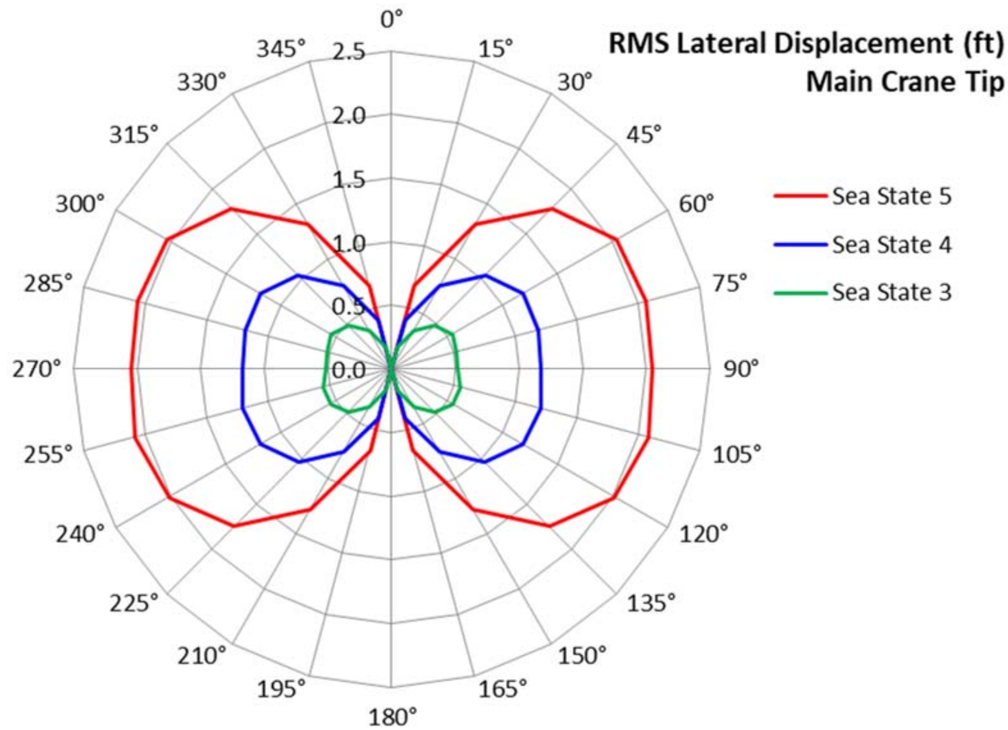


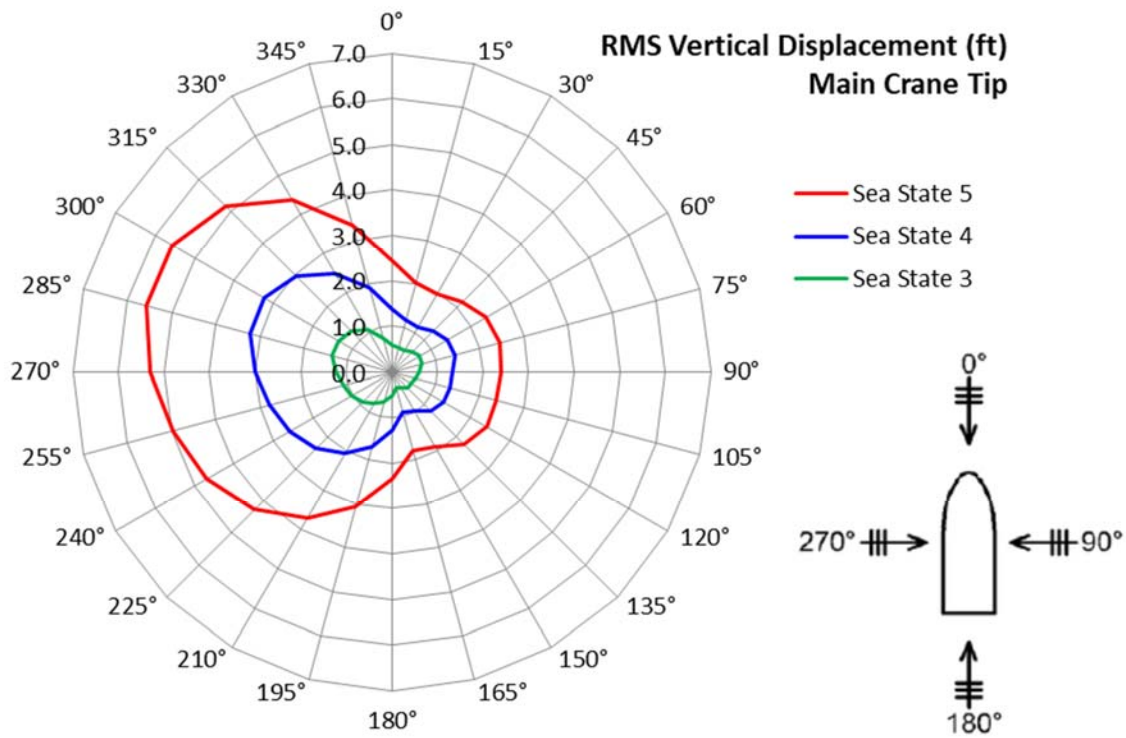


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Main Crane Tip

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

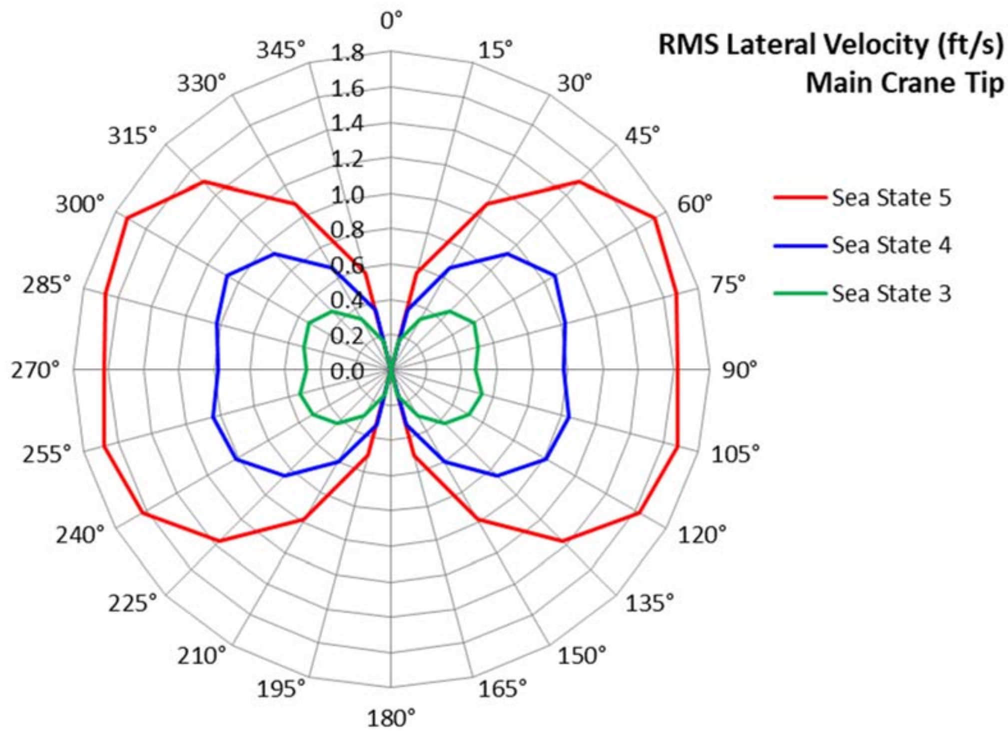


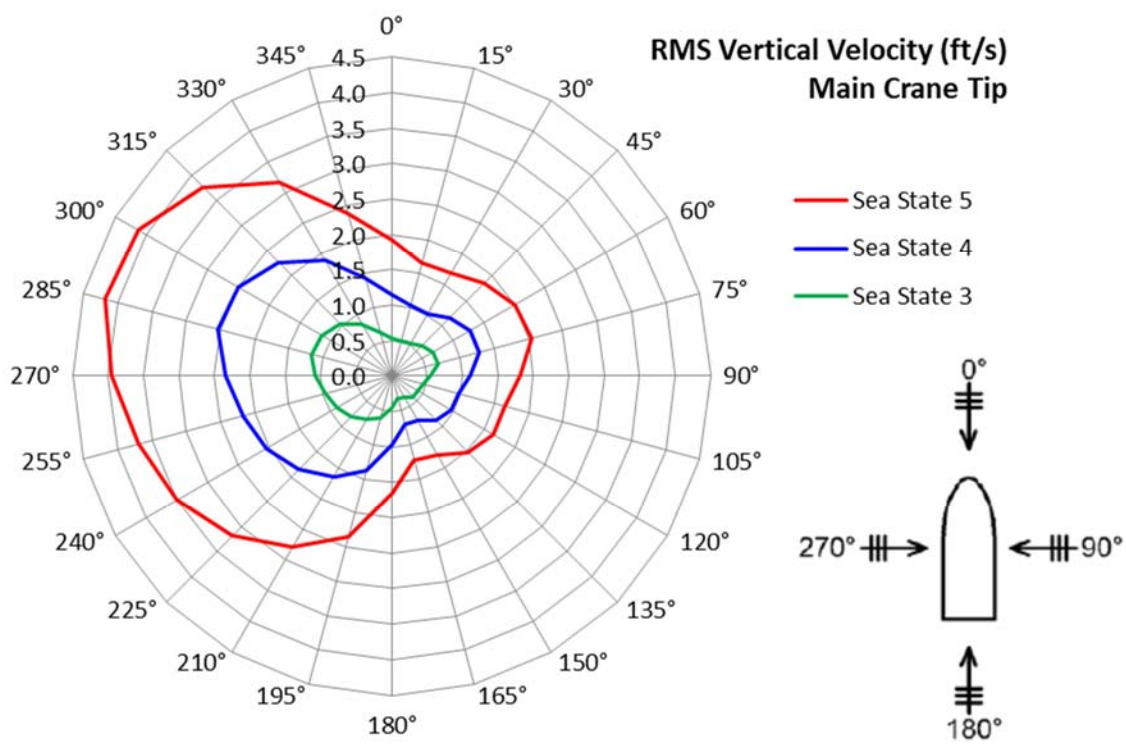


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Main Crane Tip

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

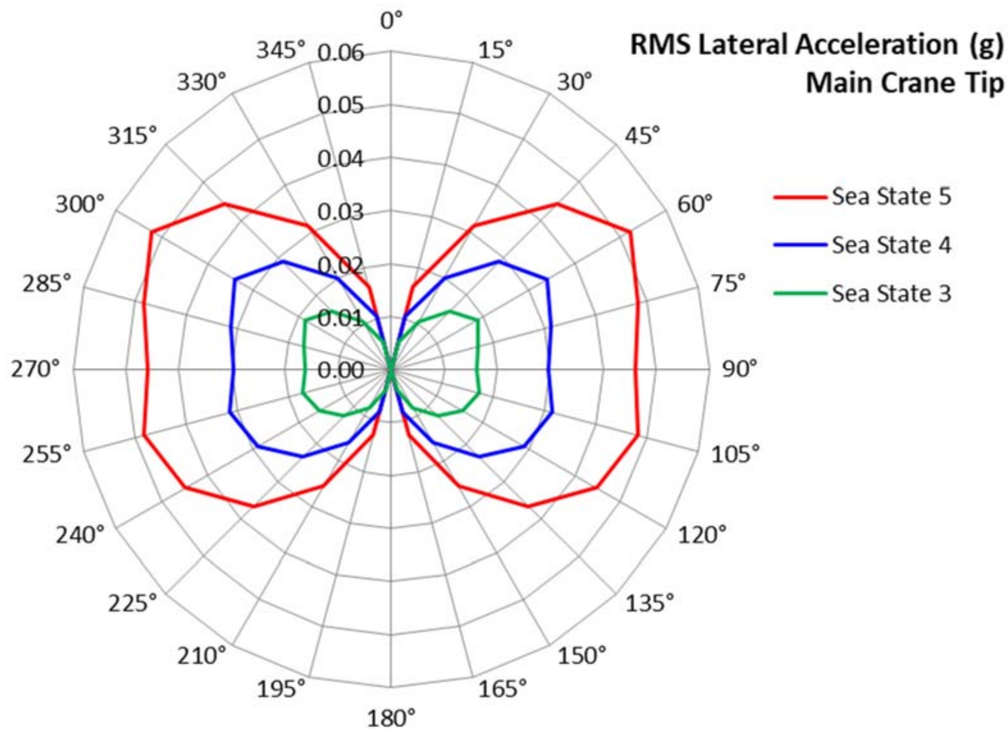


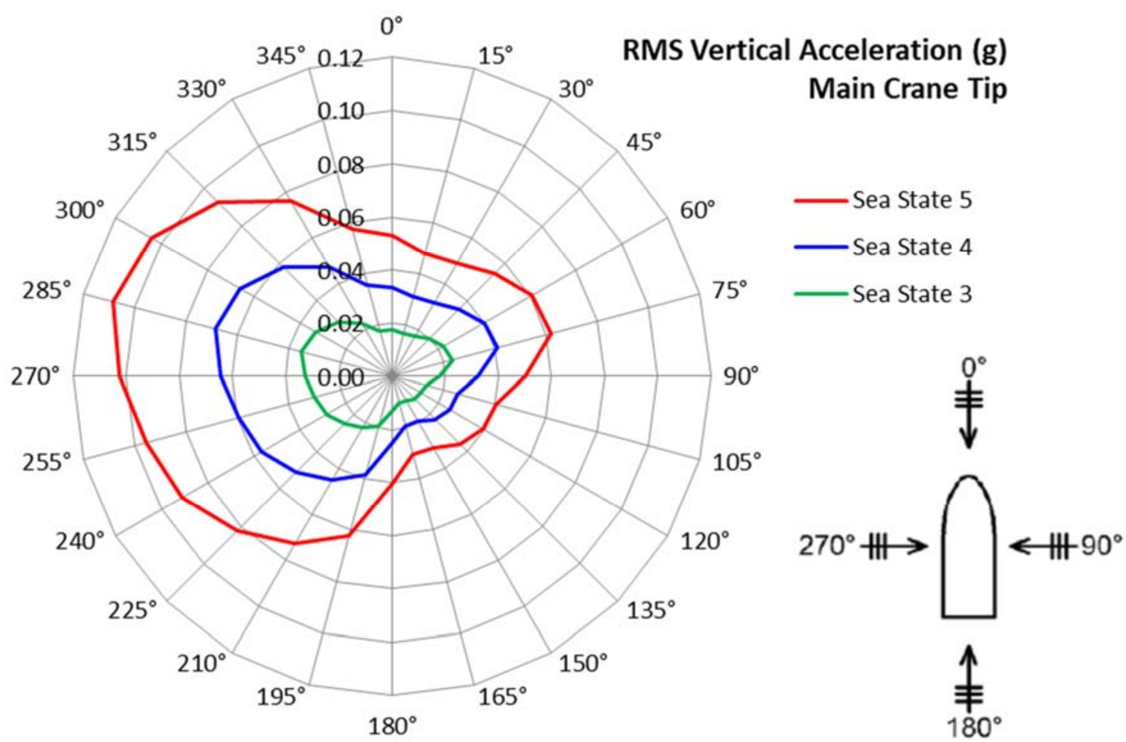


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Main Crane Tip

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

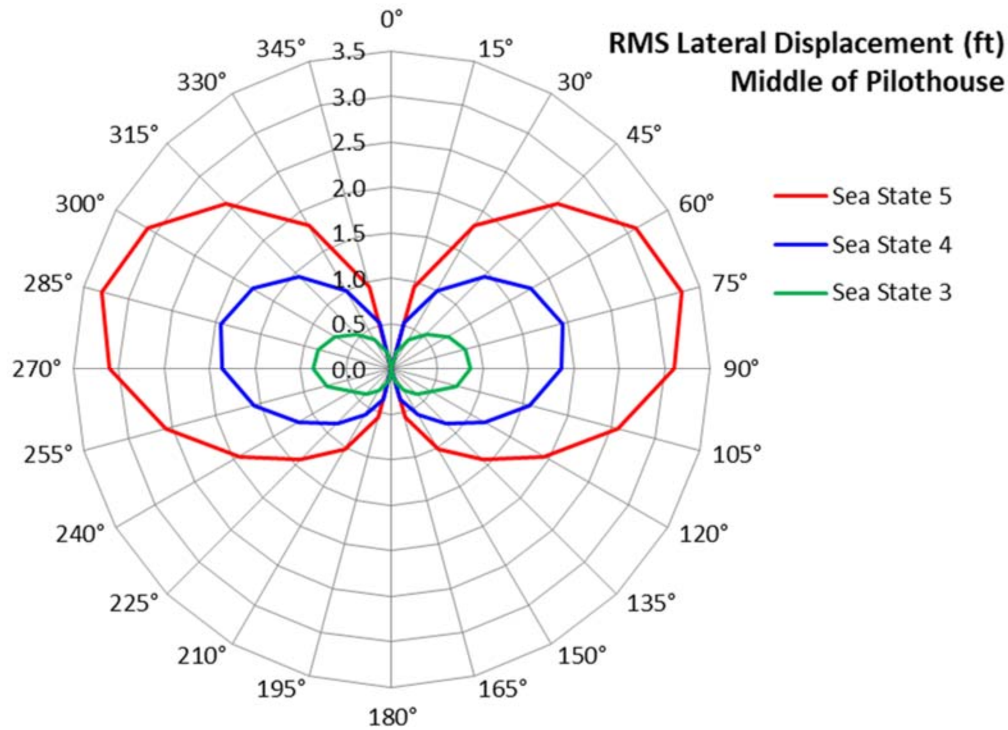


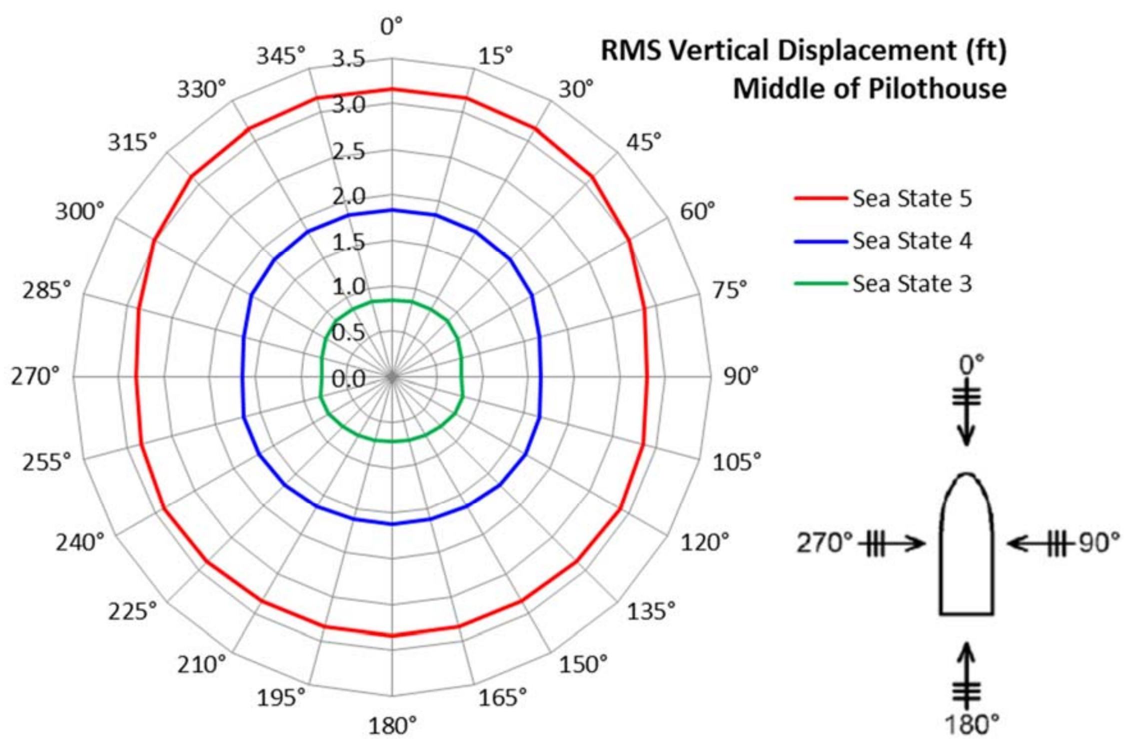


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Middle of Pilothouse

-- With Roll Stabilizers <u>Turned On</u> and <u>Full-length</u> Bilge Keel --

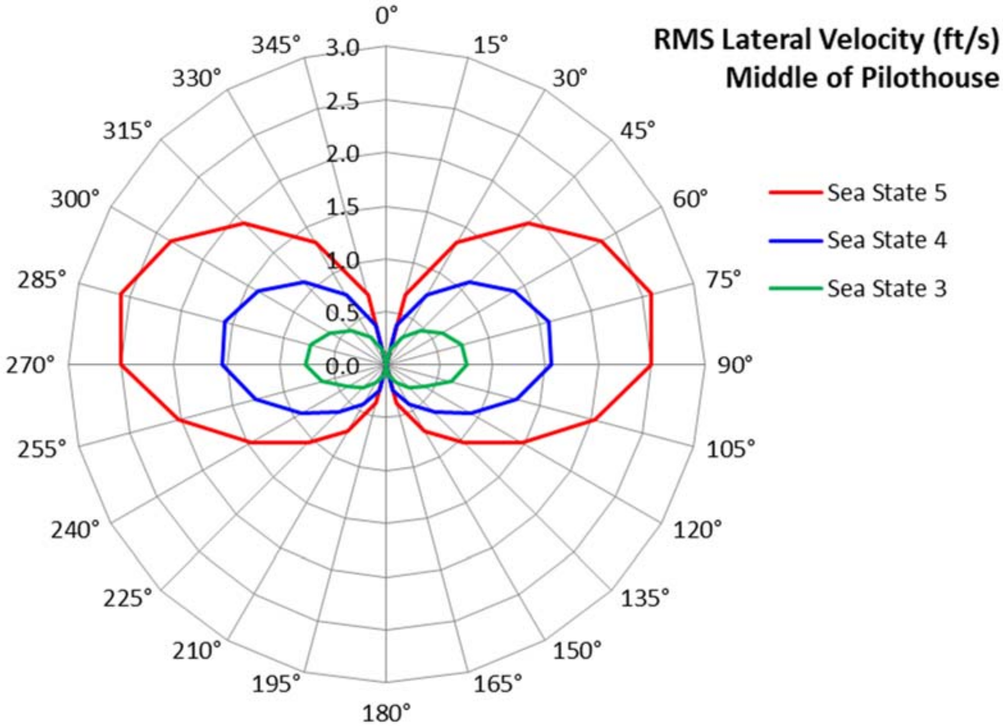


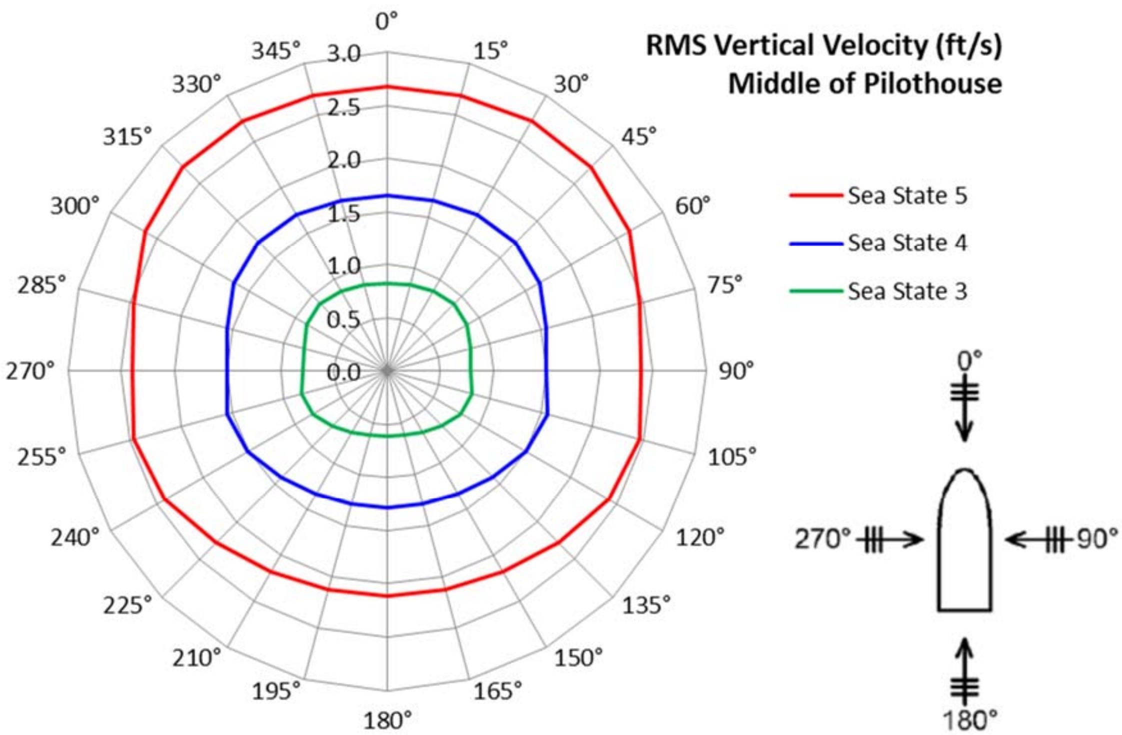


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Middle of Pilothouse

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

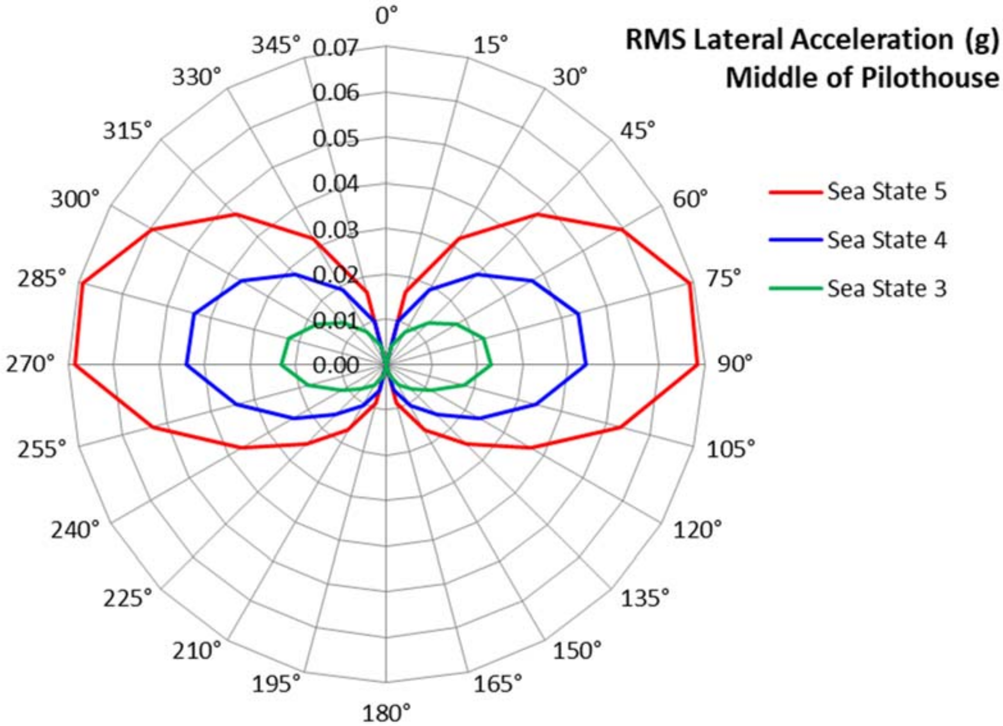


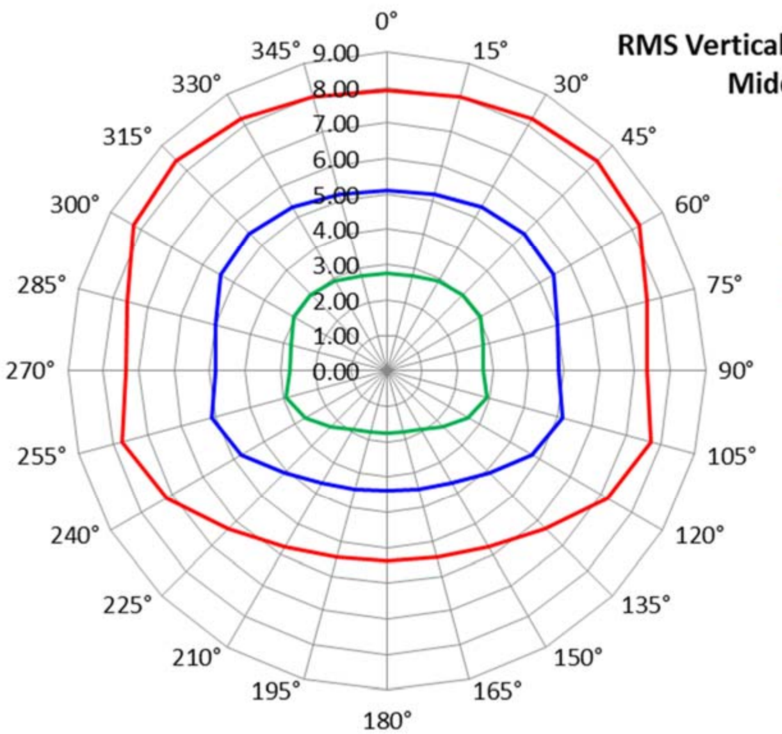


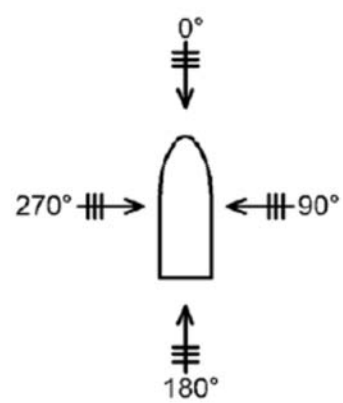
Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Middle of Pilothouse

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --



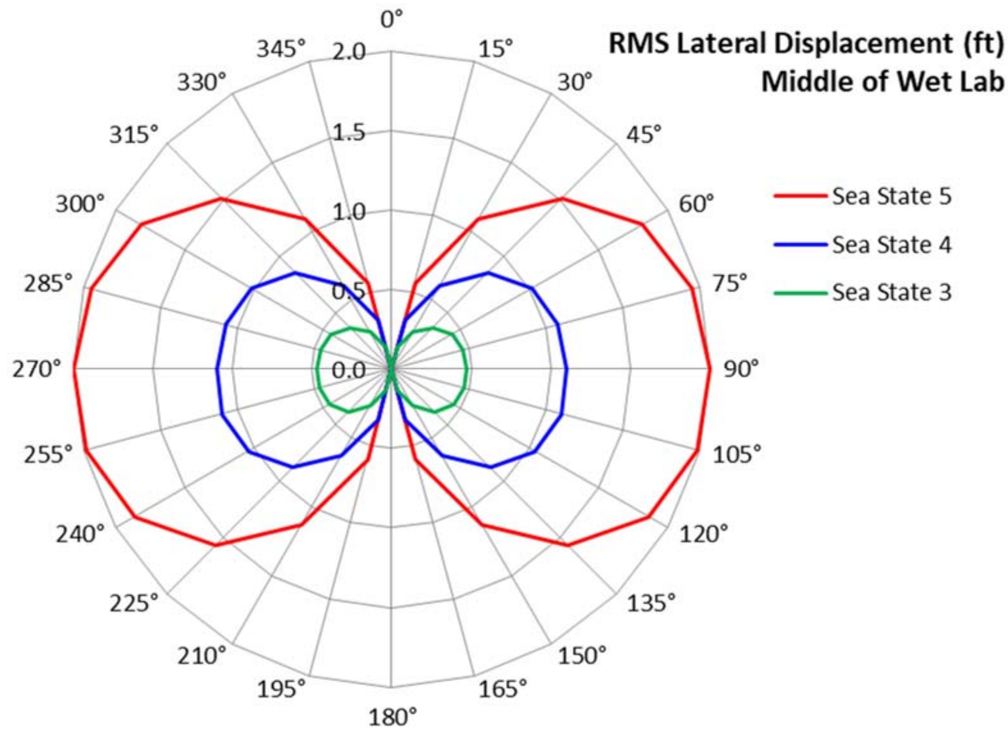


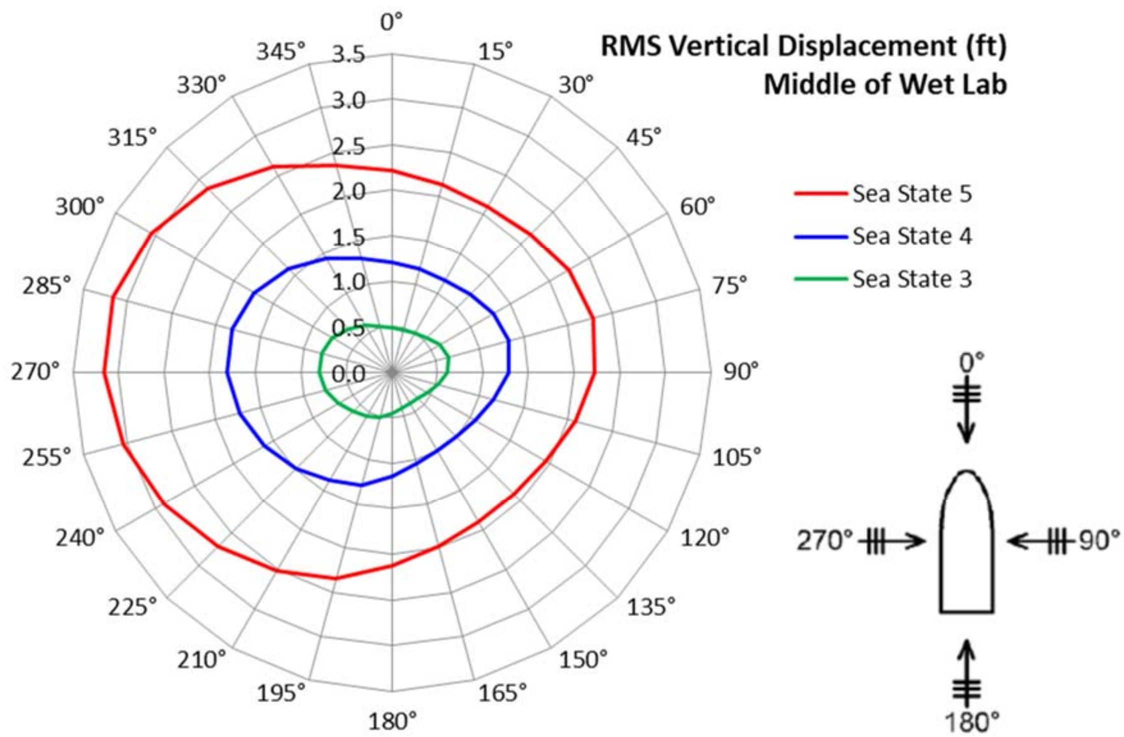


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Middle of Wet Lab

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

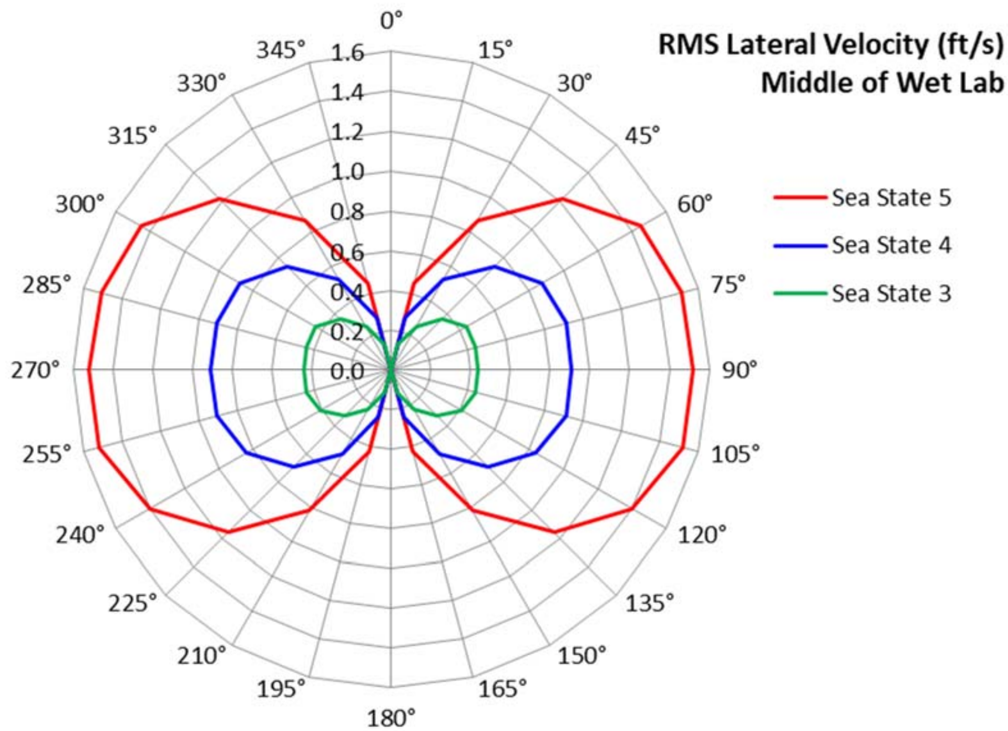


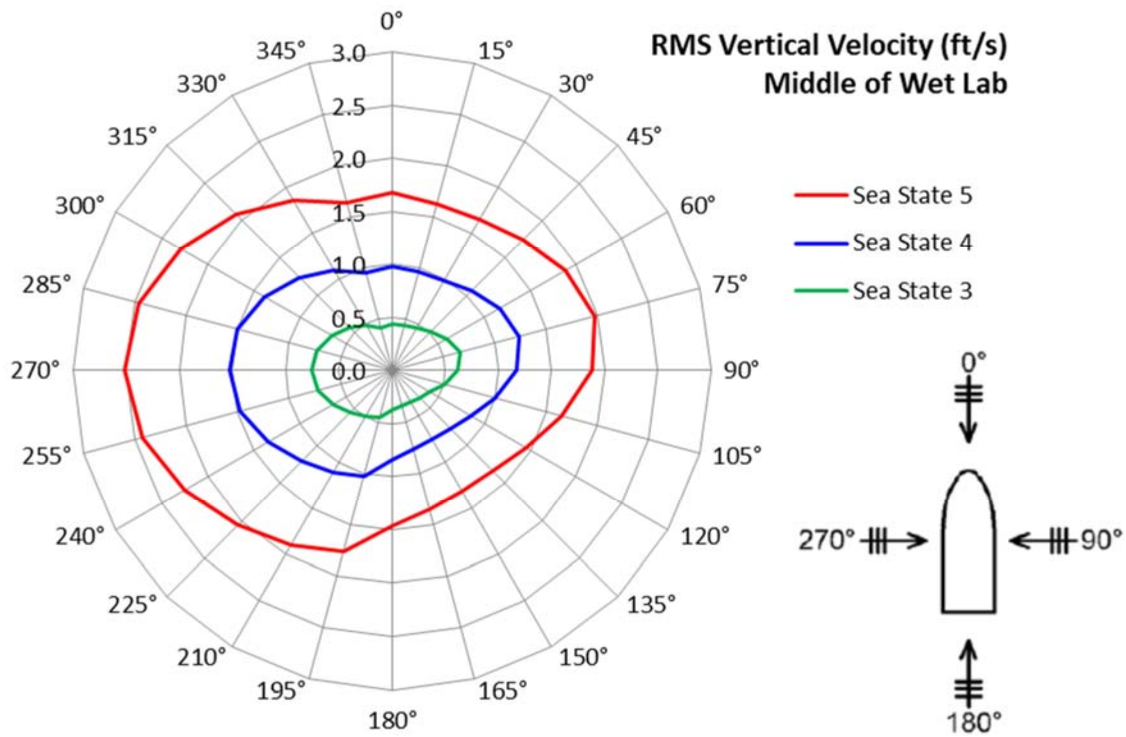


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Middle of Wet Lab

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

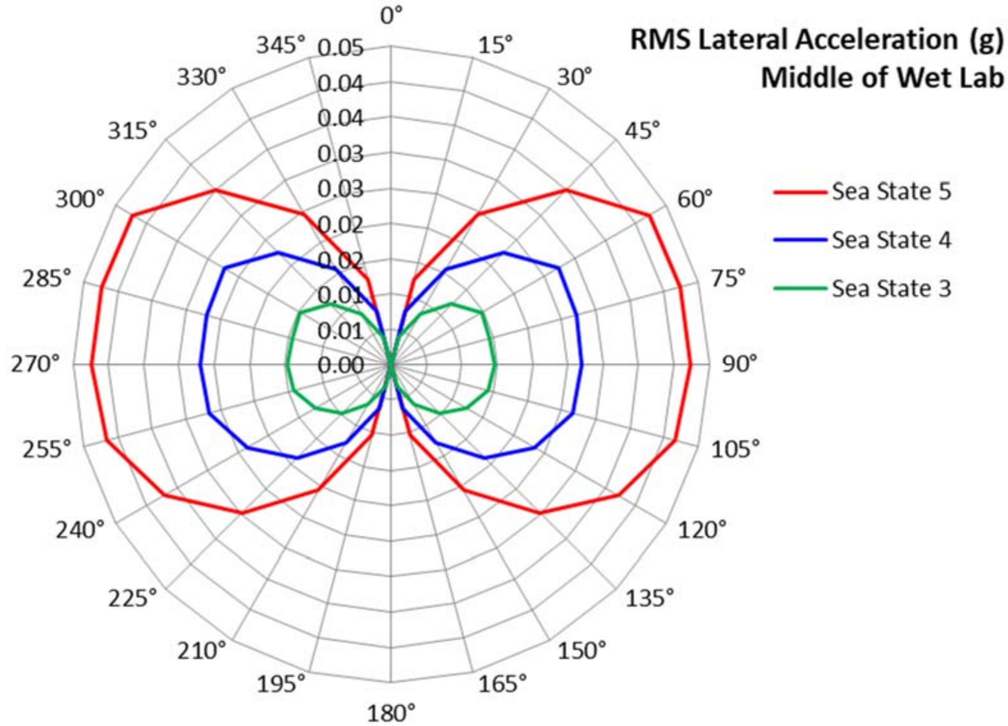


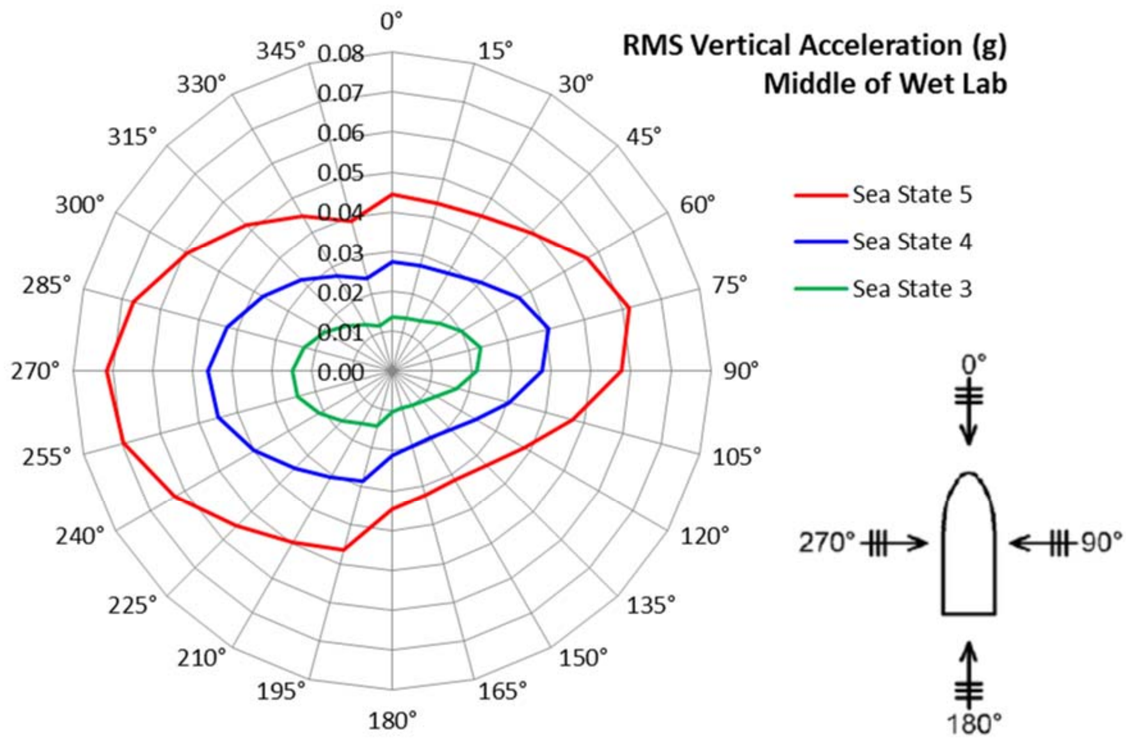


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Middle of Wet Lab

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

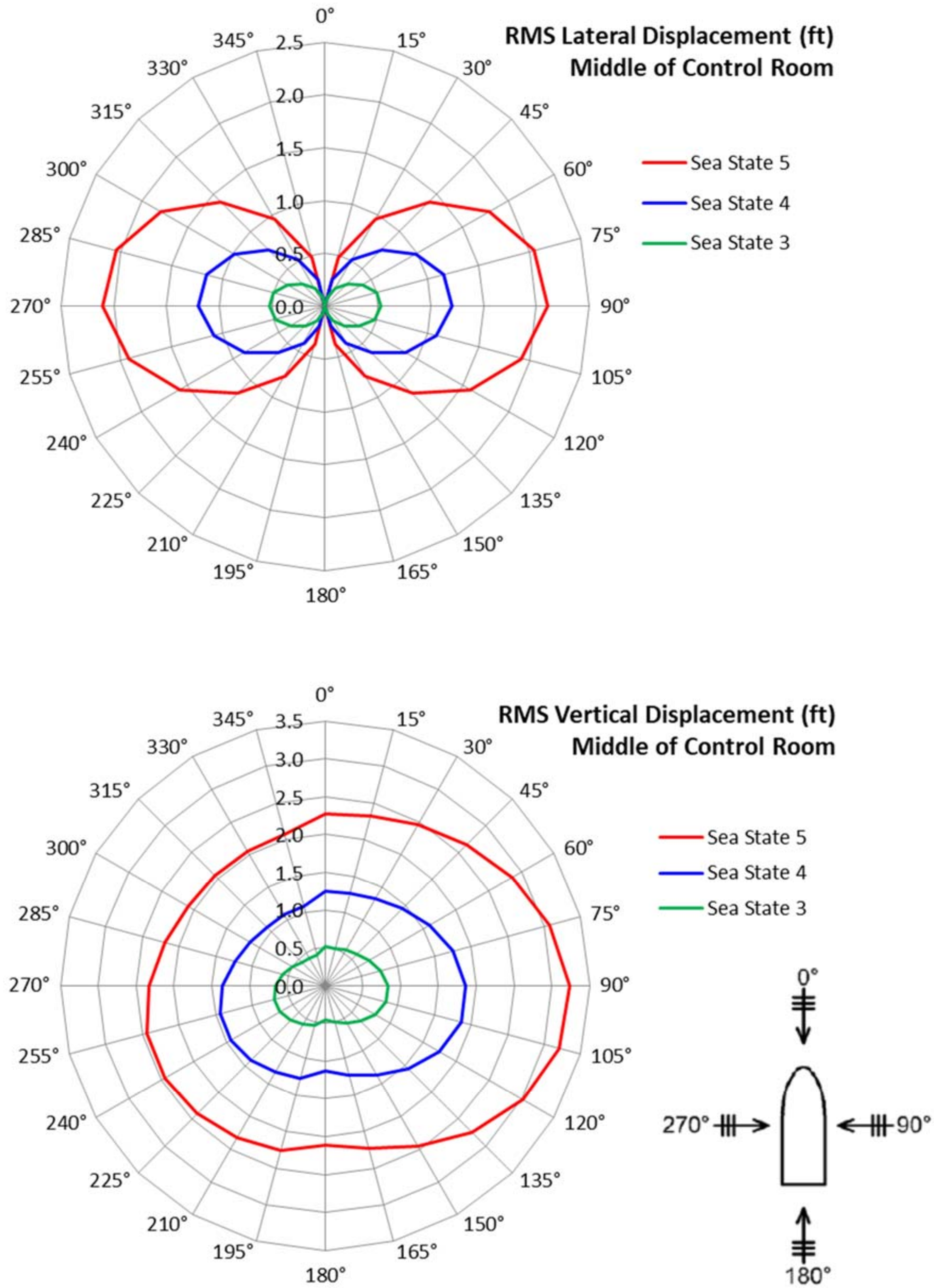




Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Middle of Control Room

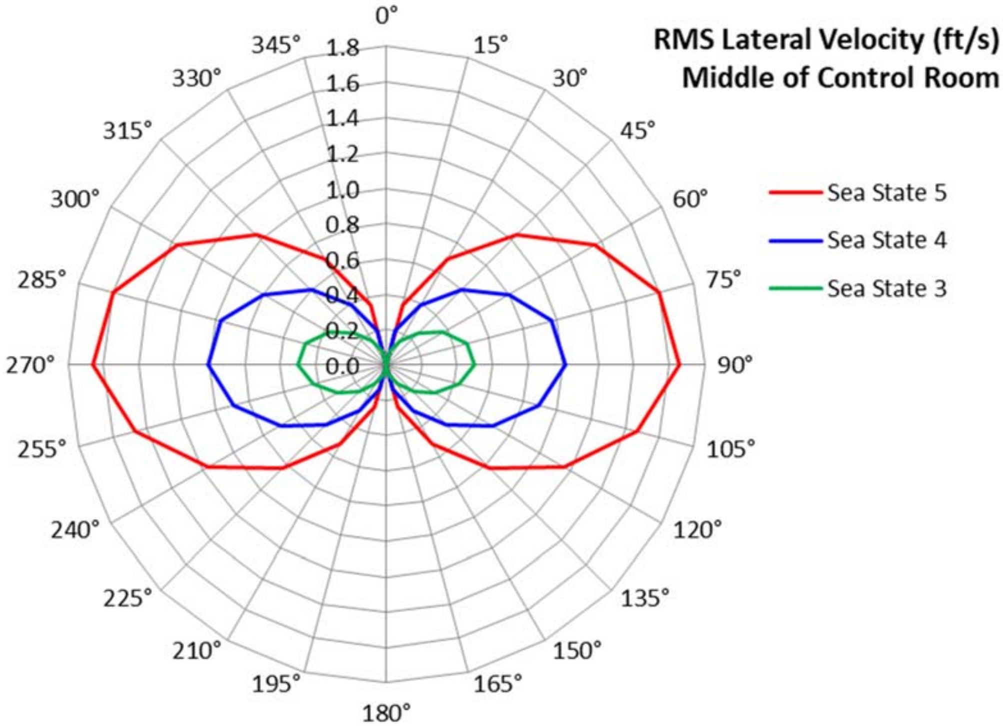
-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

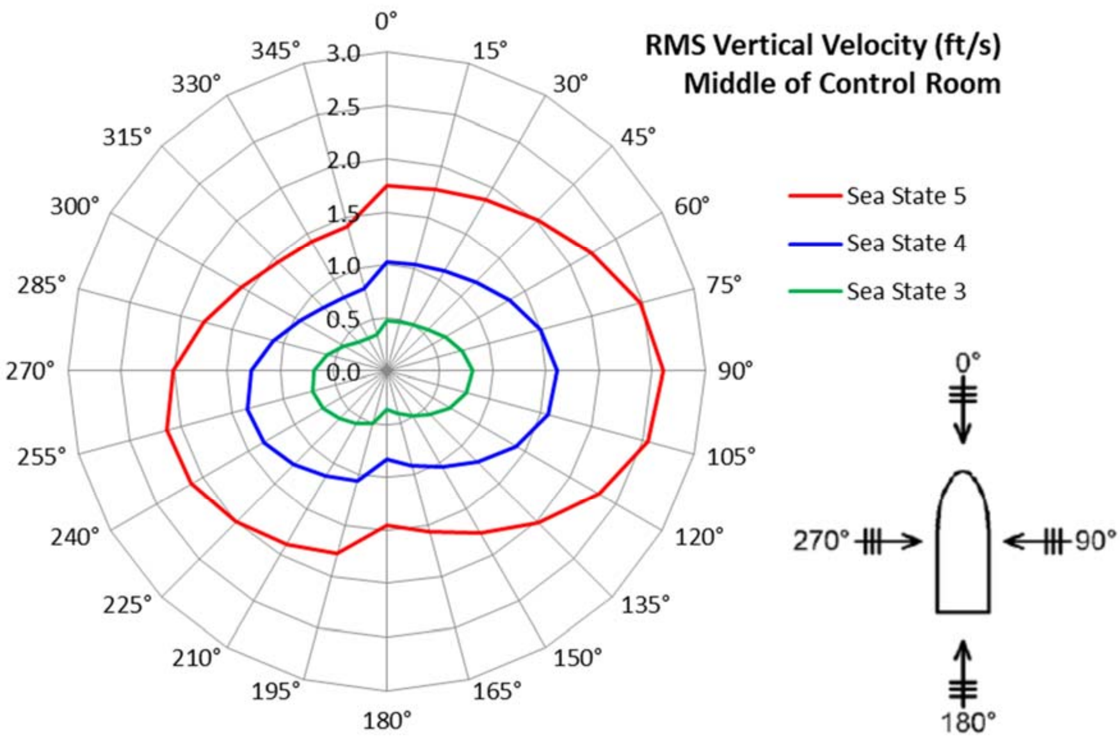


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Middle of Control Room

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

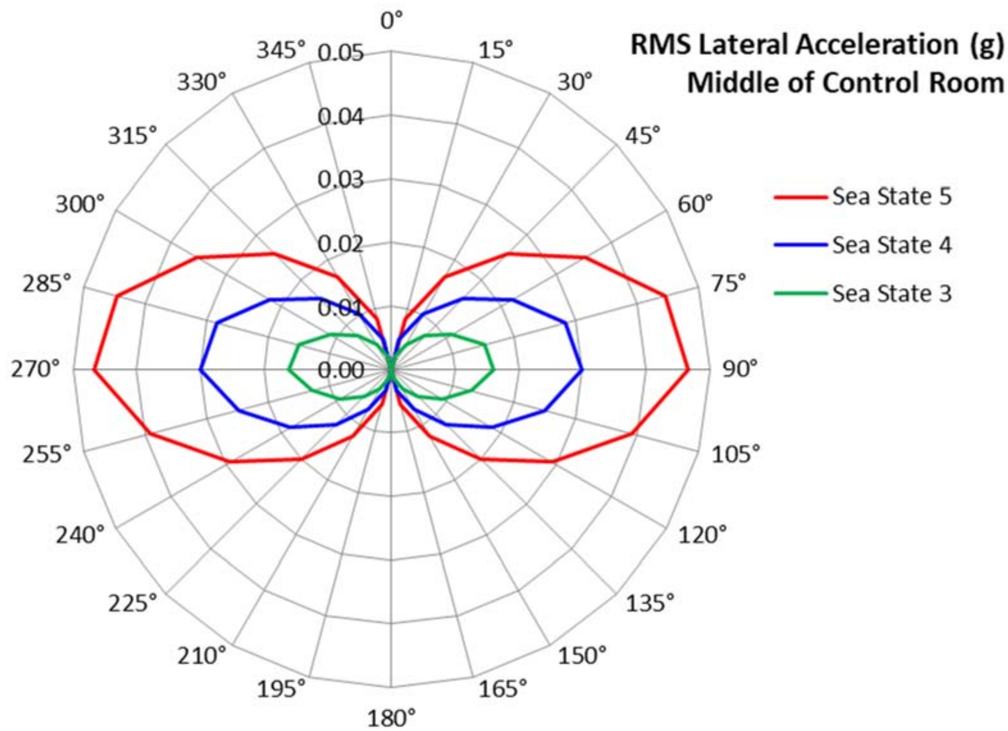


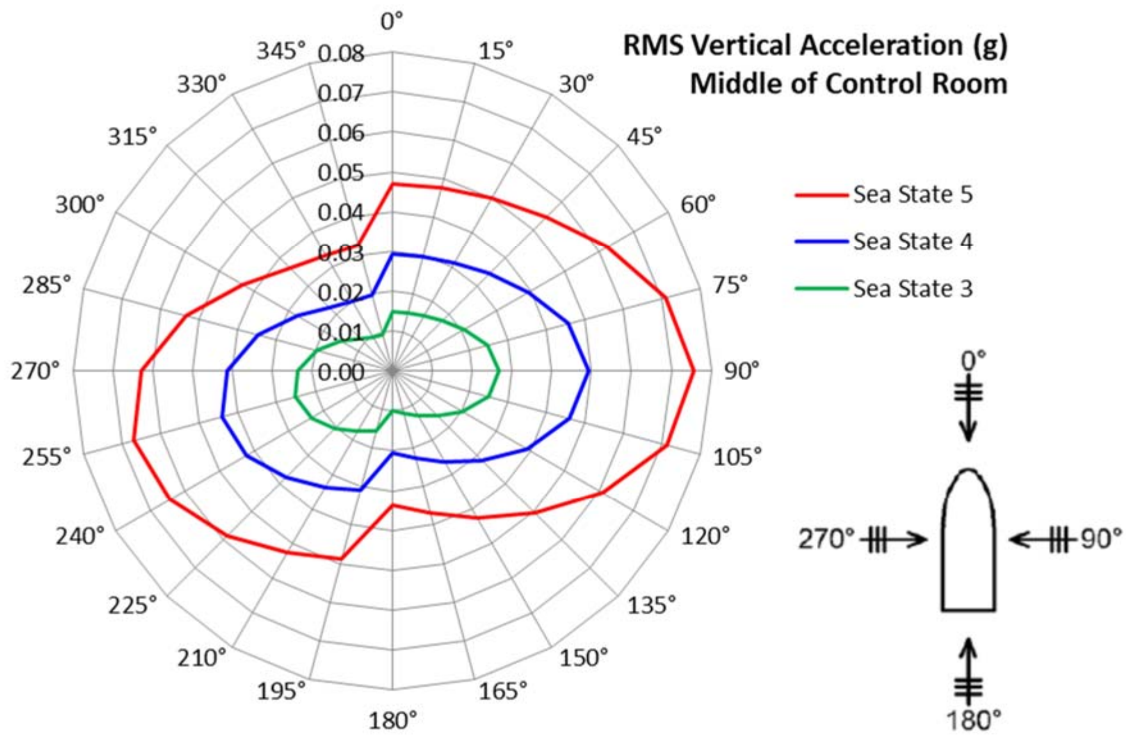


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Middle of Control Room

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

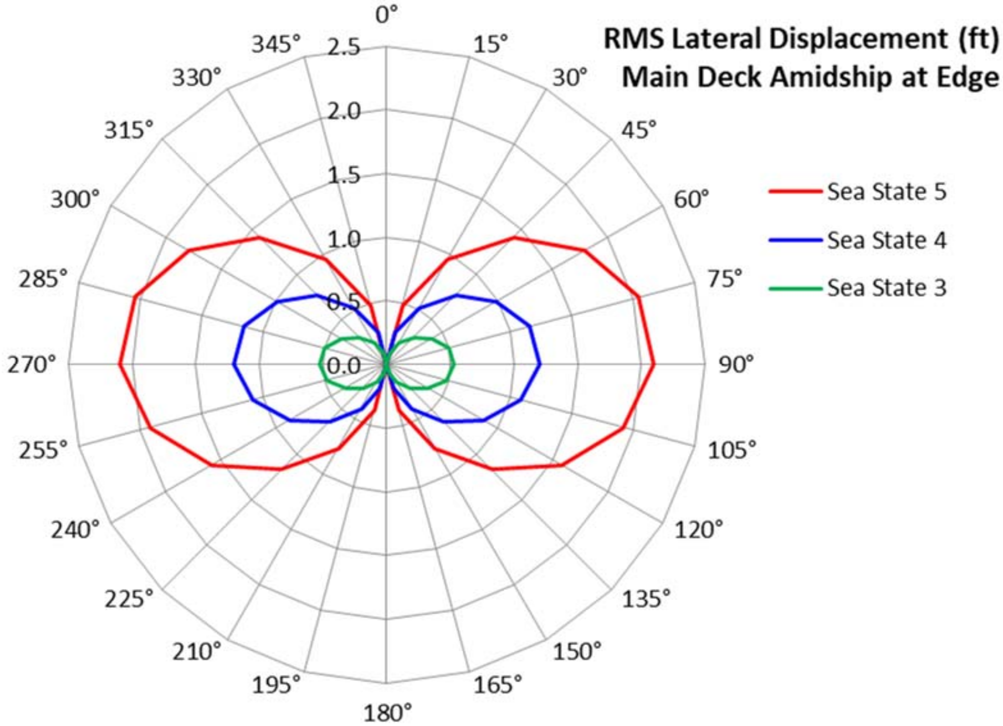


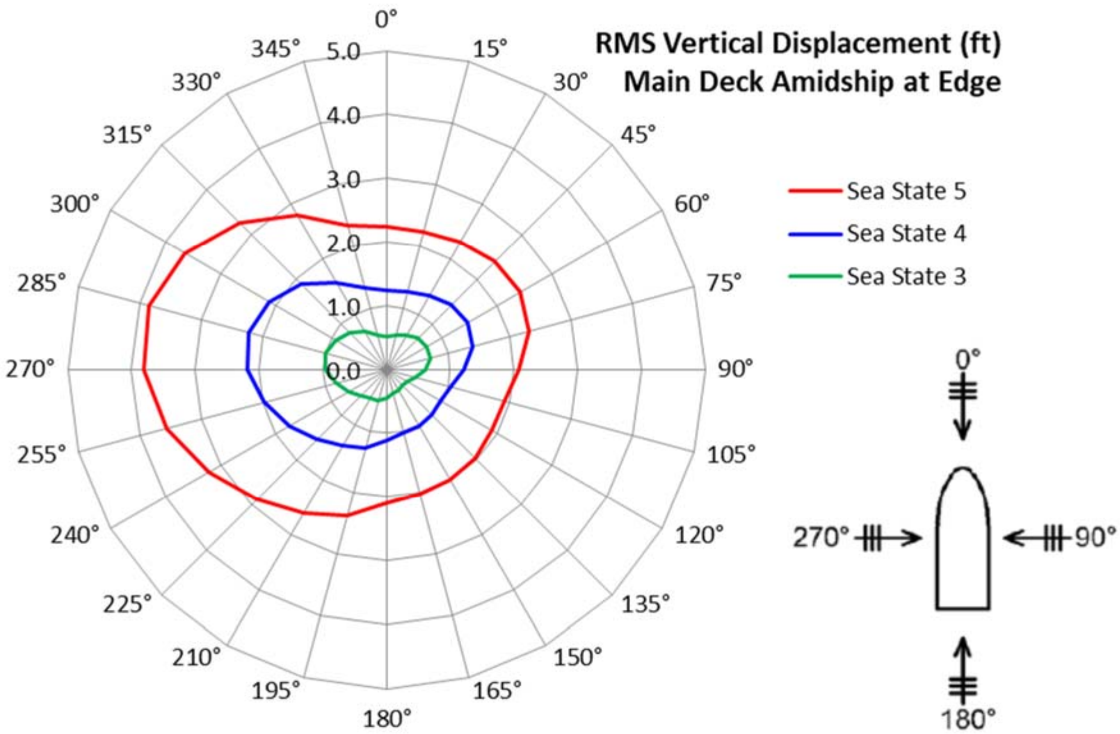


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

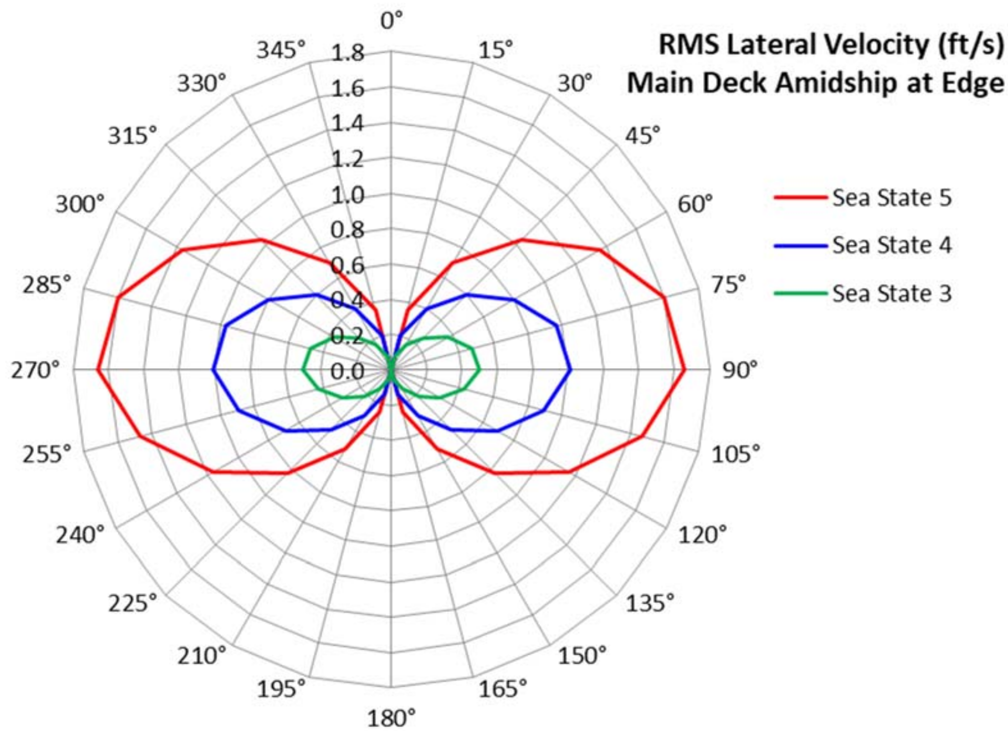


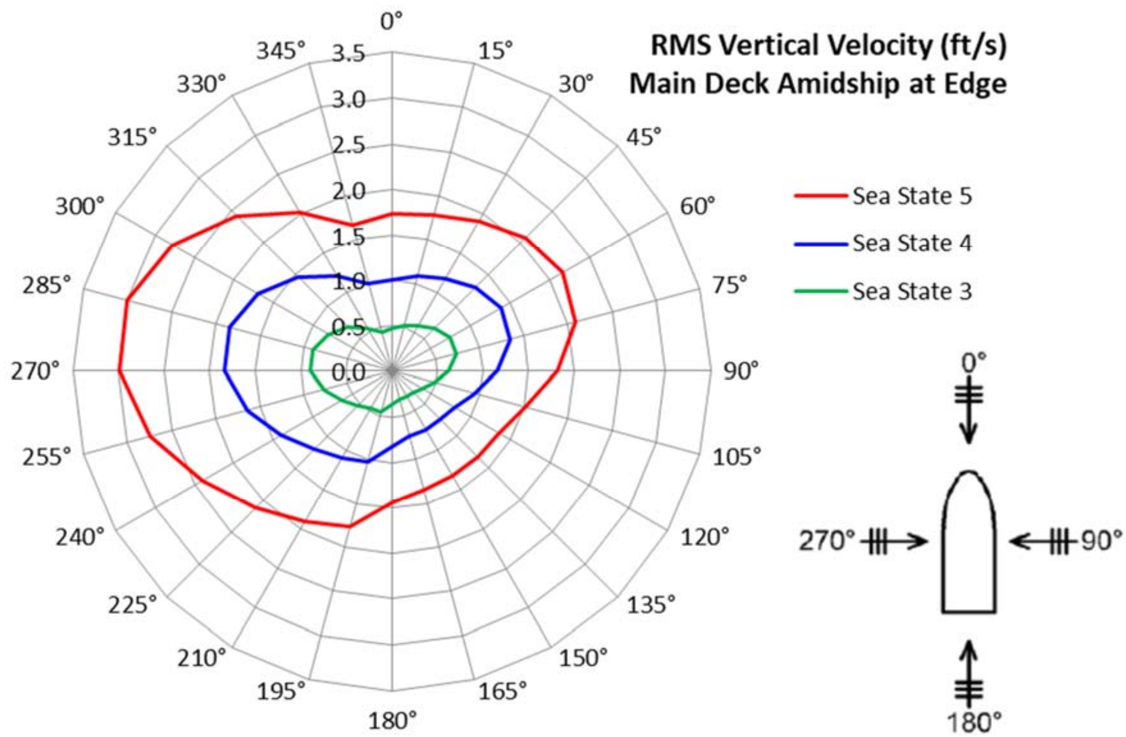


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

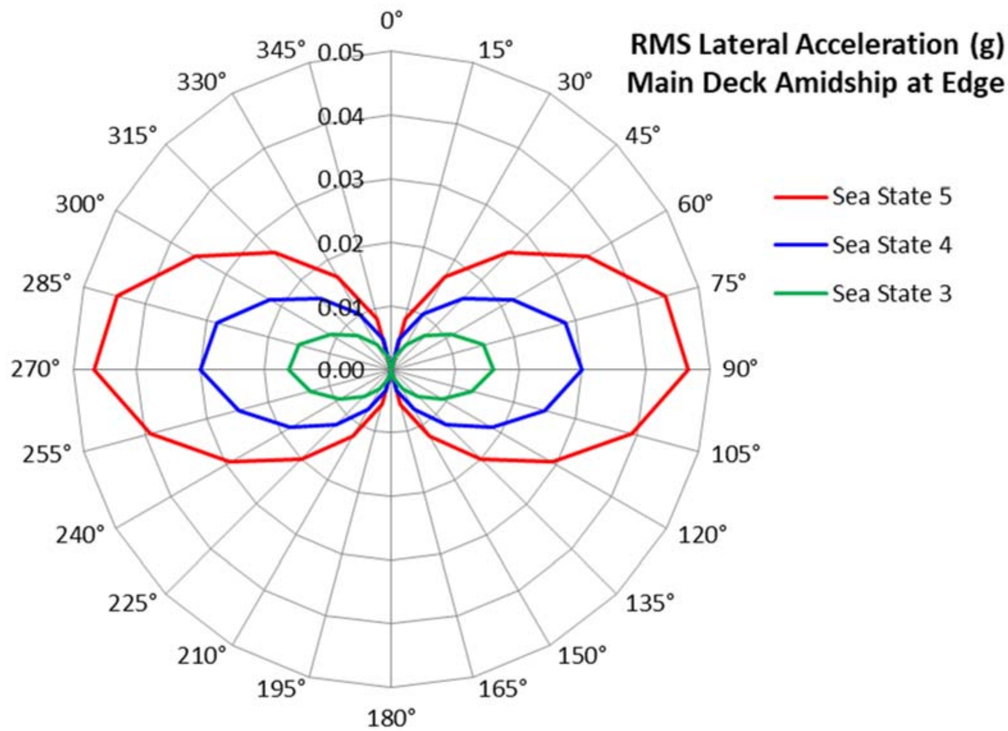


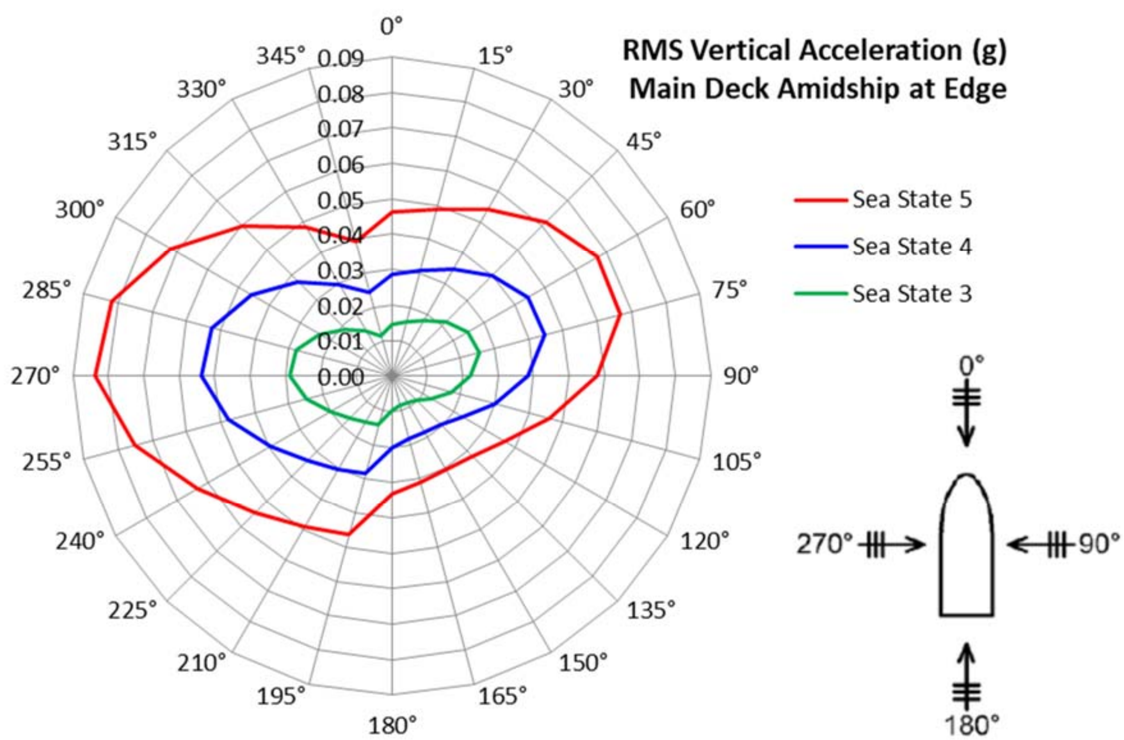


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

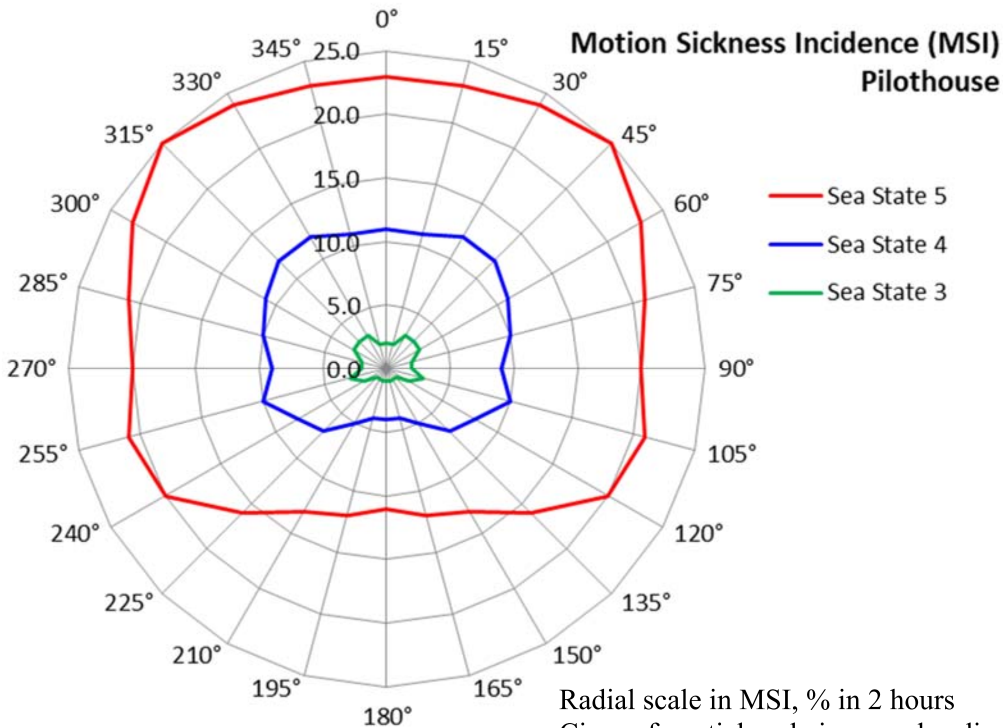




Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

Motion Sickness Incidence (MSI) in Pilothouse

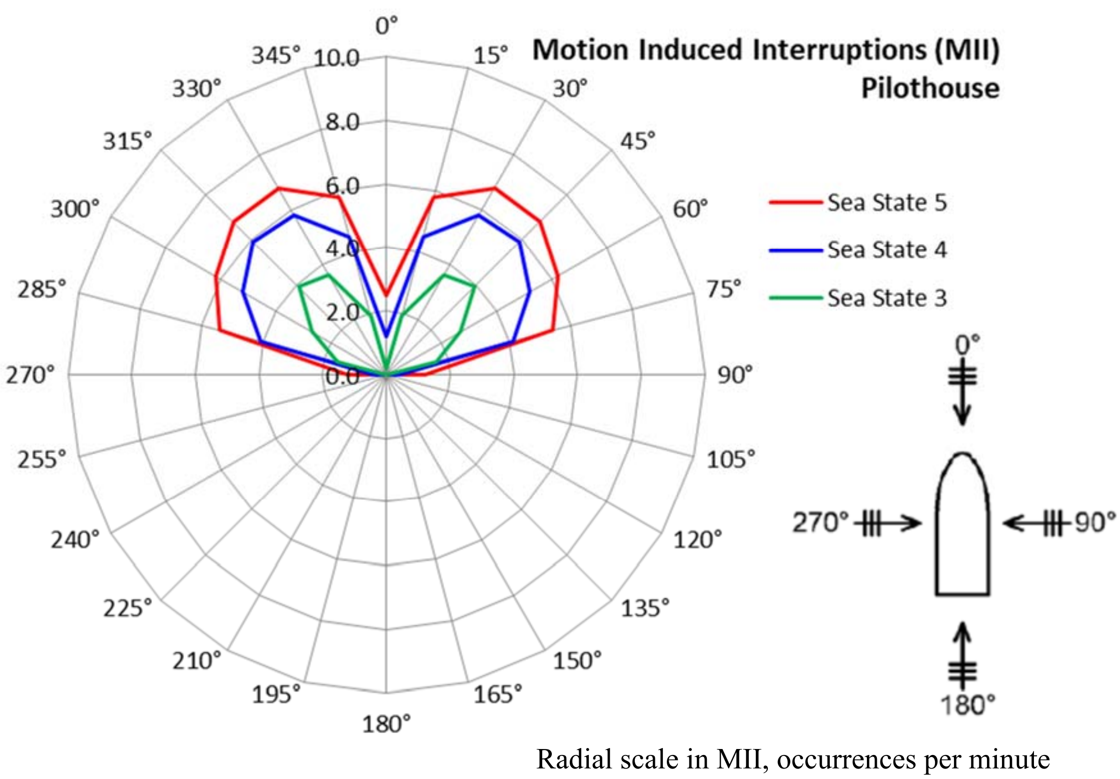
-- With Roll Stabilizers Turned On and Full-length Bilge Keel --



Radial scale in MSI, % in 2 hours
Circumferential scale in wave heading (deg)

Motion Induced Interruptions (MII) in Pilothouse

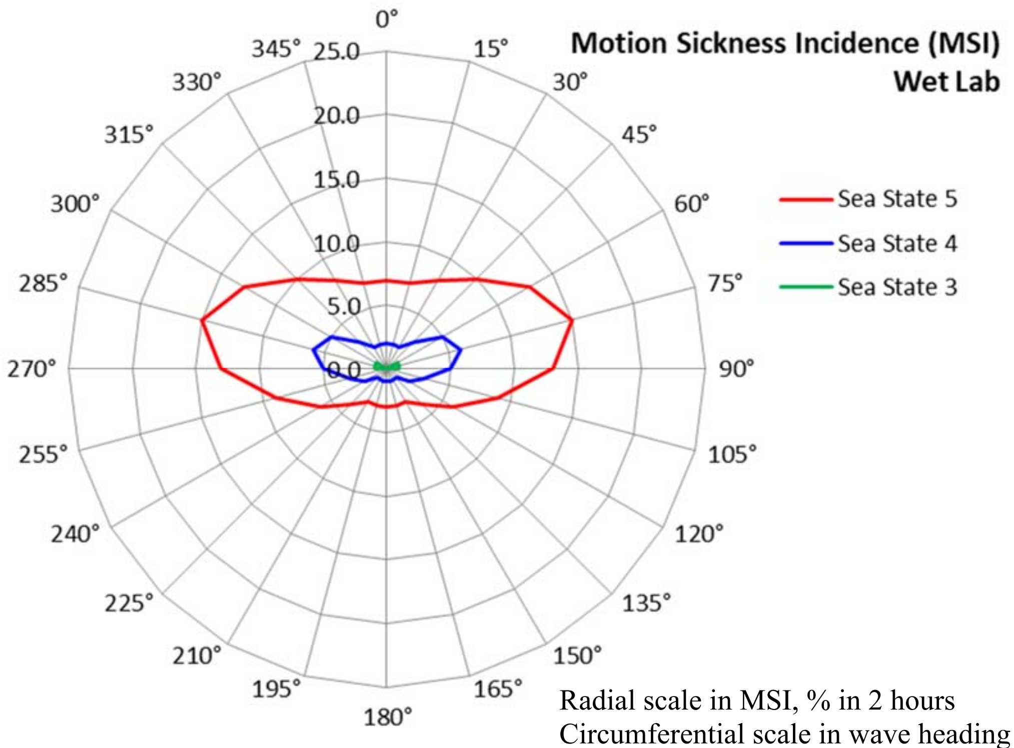
-- With Roll Stabilizers Turned On and Full-length Bilge Keel --



Radial scale in MII, occurrences per minute
Circumferential scale in wave heading (deg)

Motion Sickness Incidence (MSI) in Wet Lab

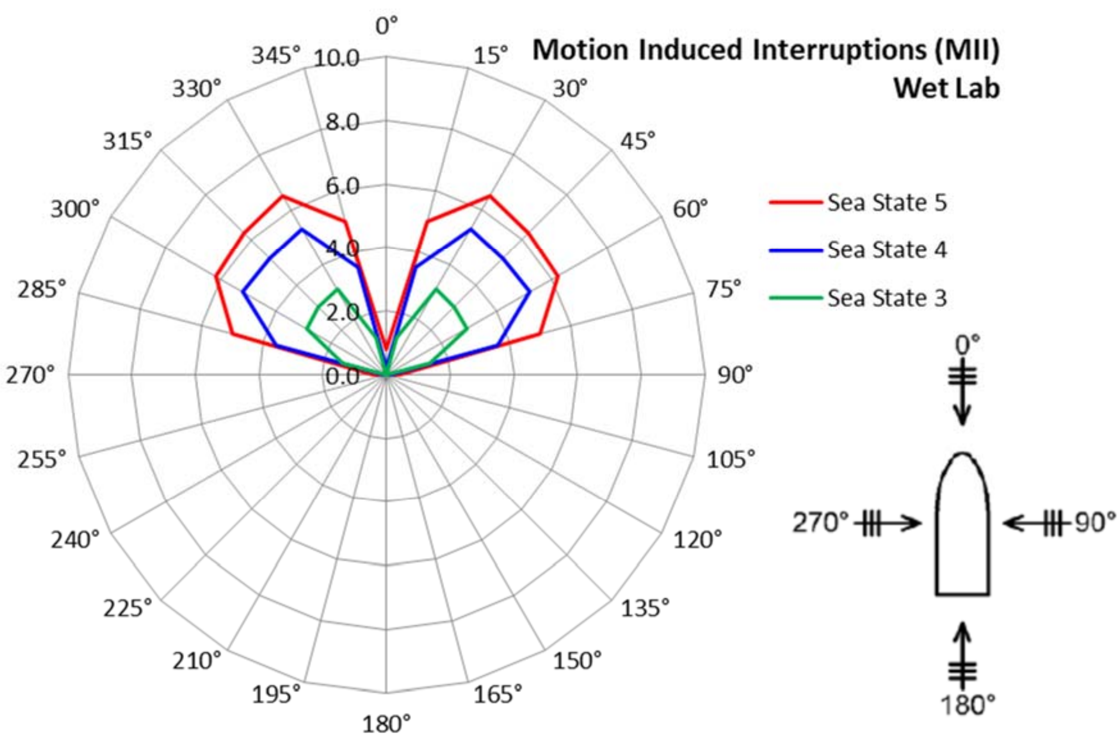
-- With Roll Stabilizers Turned On and Full-length Bilge Keel --



Radial scale in MSI, % in 2 hours
Circumferential scale in wave heading (deg)

Motion Induced Interruptions (MII) in Wet Lab

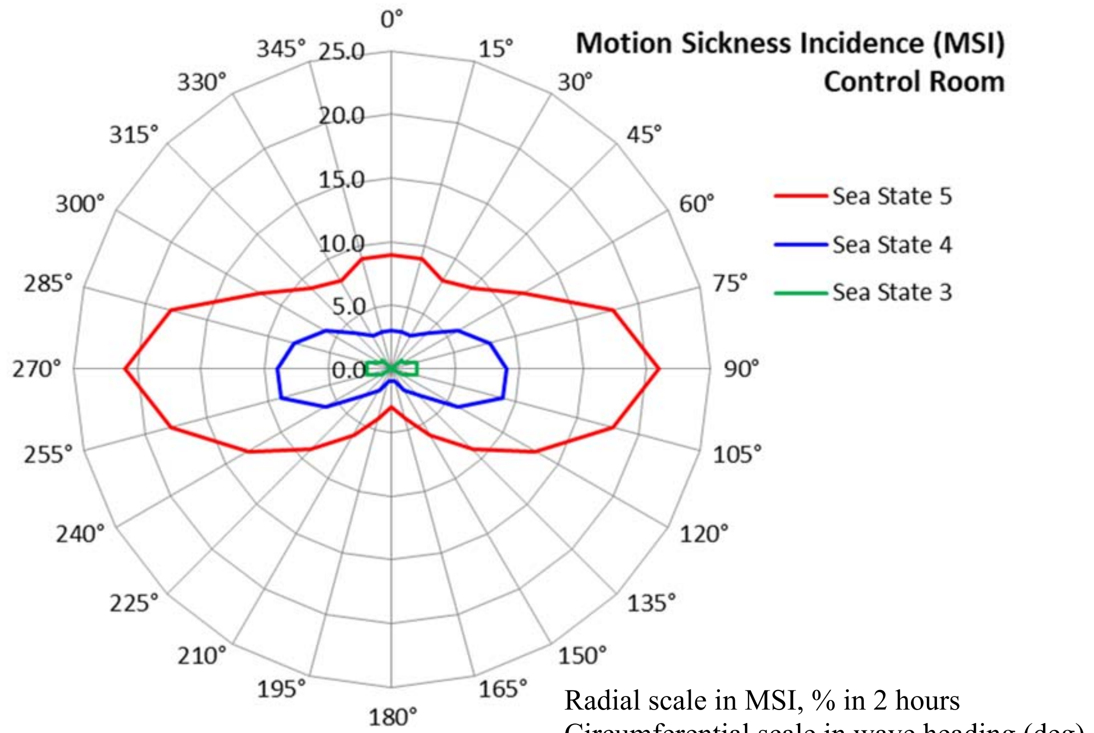
-- With Roll Stabilizers Turned On and Full-length Bilge Keel --



Radial scale in MII, occurrences per minute
Circumferential scale in wave heading (deg)

Motion Sickness Incidence (MSI) in Control Room

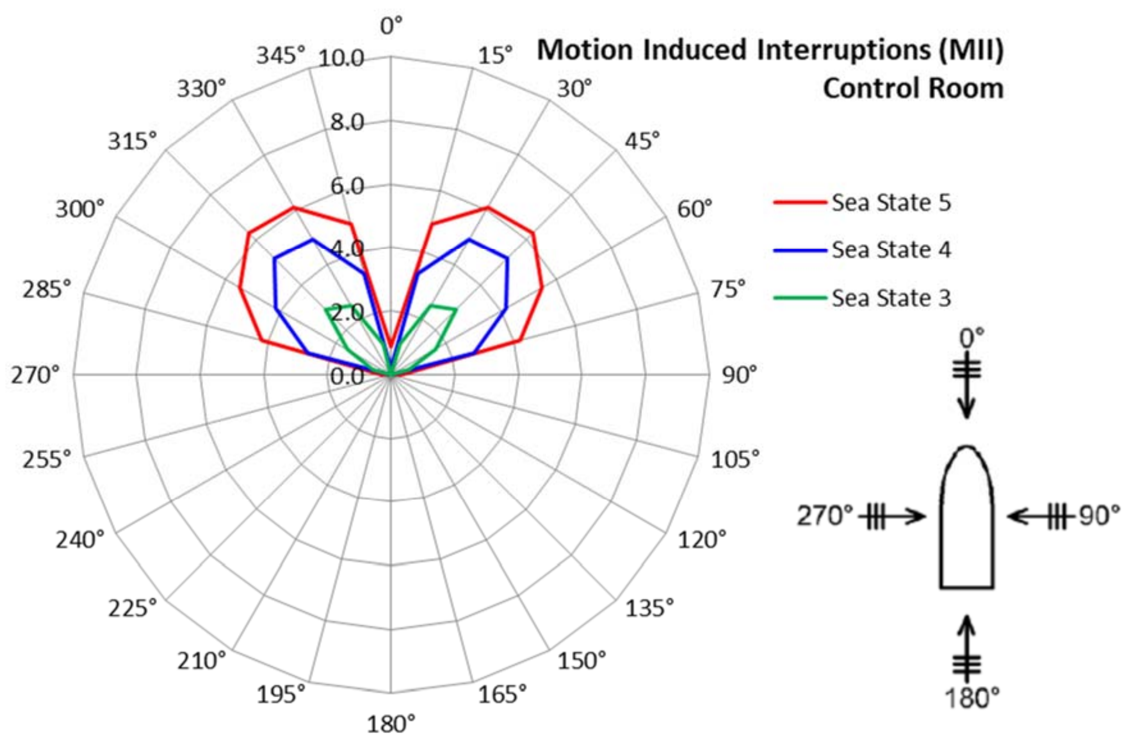
-- With Roll Stabilizers Turned On and Full-length Bilge Keel --



Radial scale in MSI, % in 2 hours
Circumferential scale in wave heading (deg)

Motion Induced Interruptions (MII) in Control Room

-- With Roll Stabilizers Turned On and Full-length Bilge Keel --

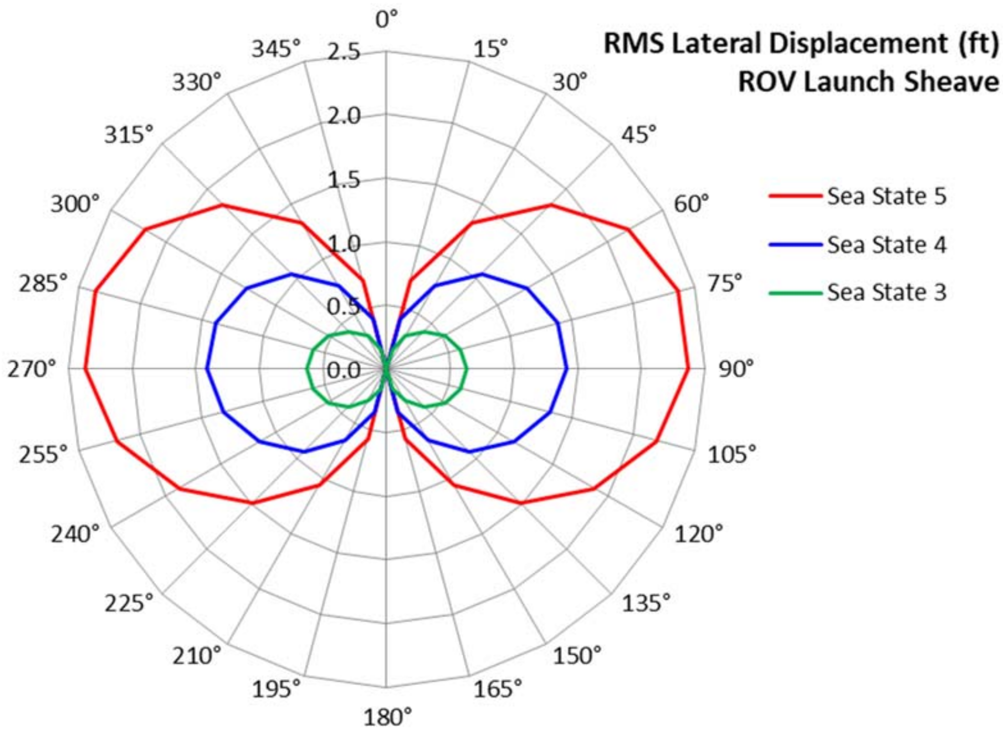


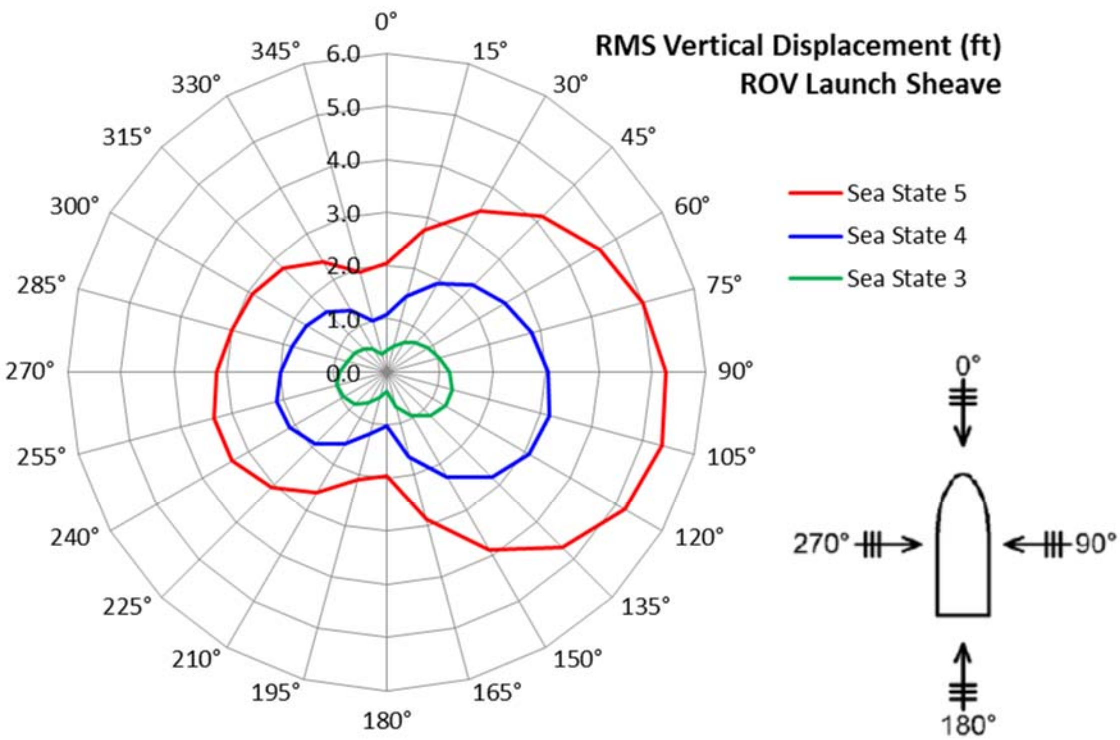
Radial scale in MII, occurrences per minute
Circumferential scale in wave heading (deg)

Appendix B Polar Diagrams – Vessel with Roll Stabilizers Turned Off and with Full-Length Bilge Keel

RMS Displacements at ROV Launch Sheave

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --

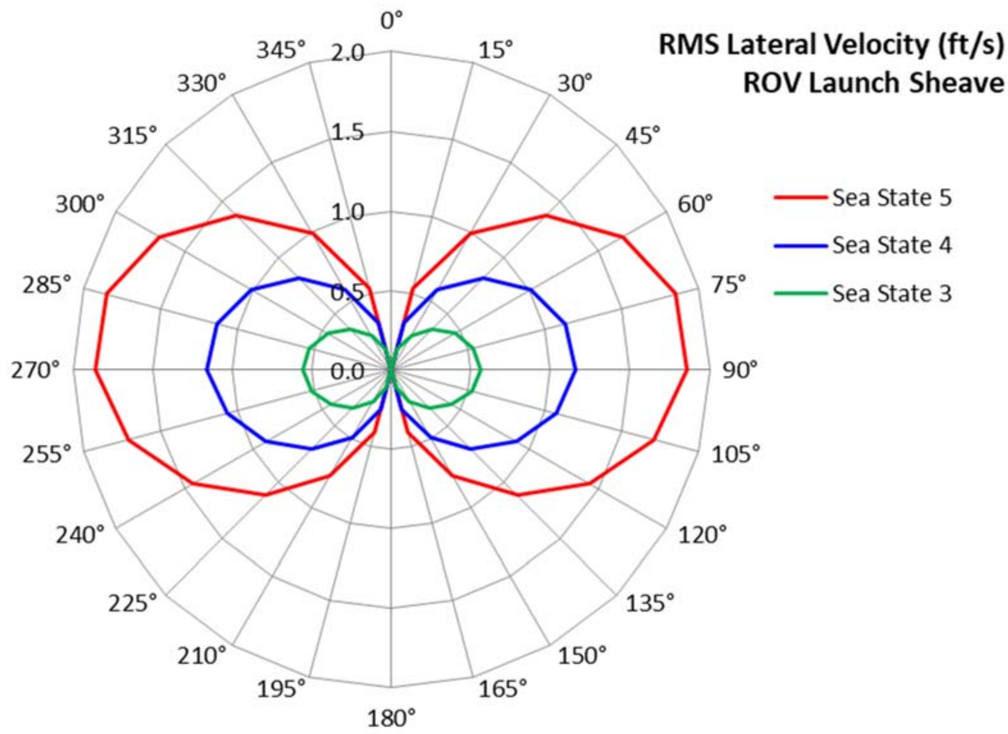


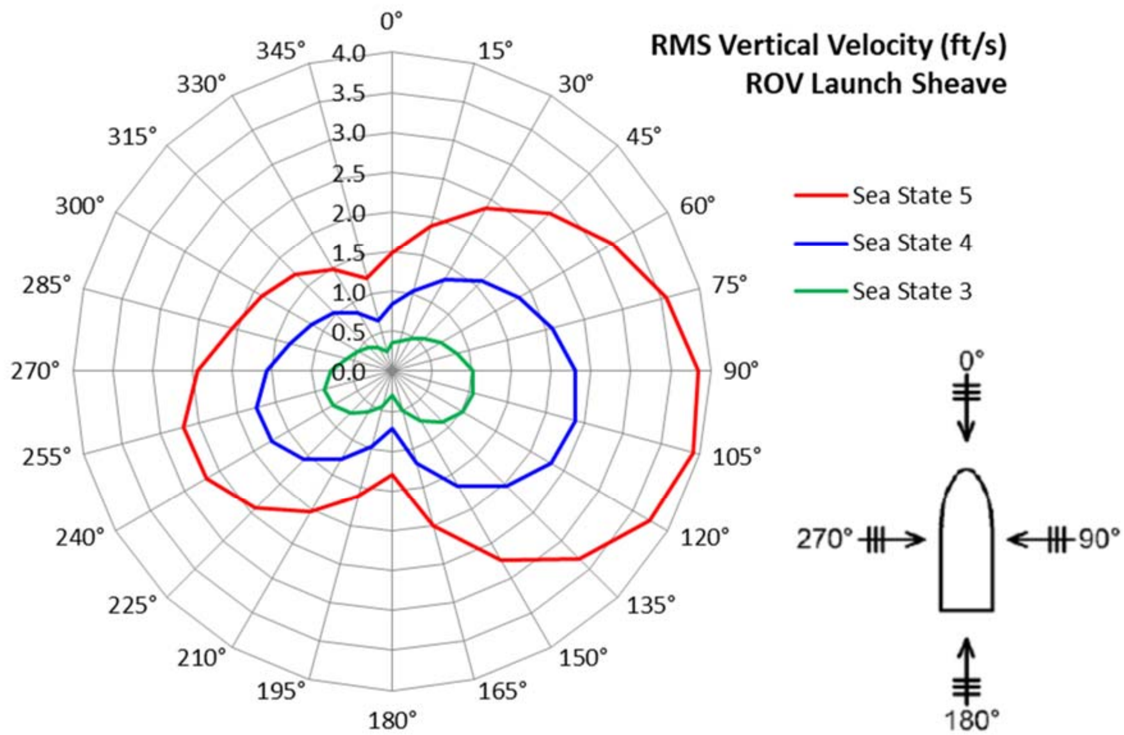


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at ROV Launch Sheave

-- With Roll Stabilizers <u>Turned Off</u> and <u>Full-length</u> Bilge Keel --

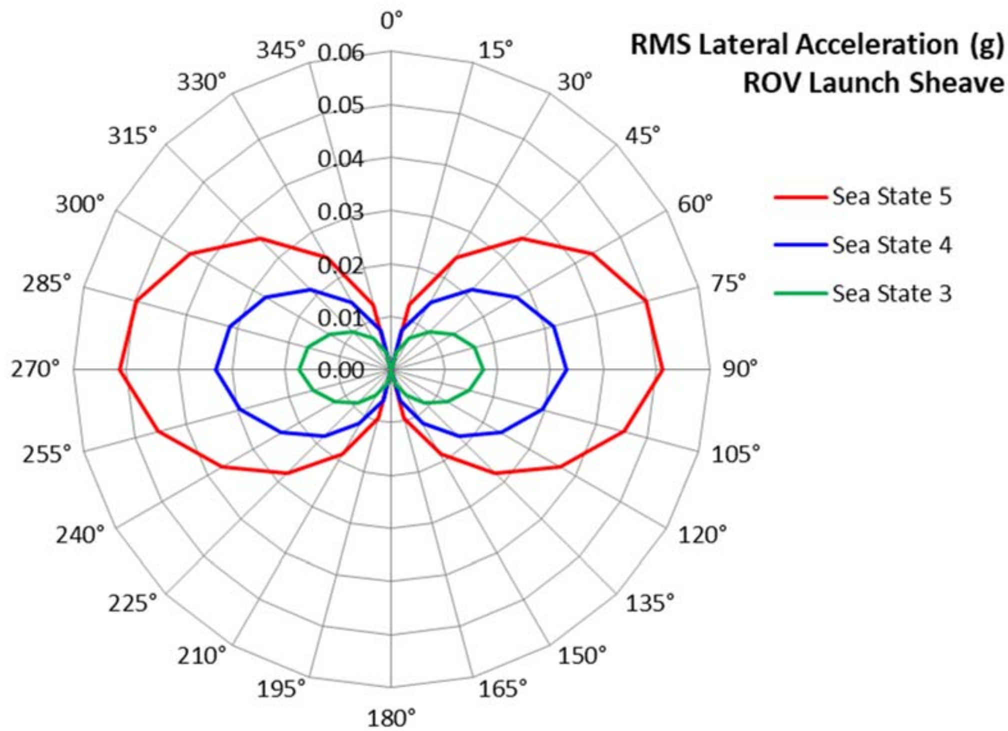


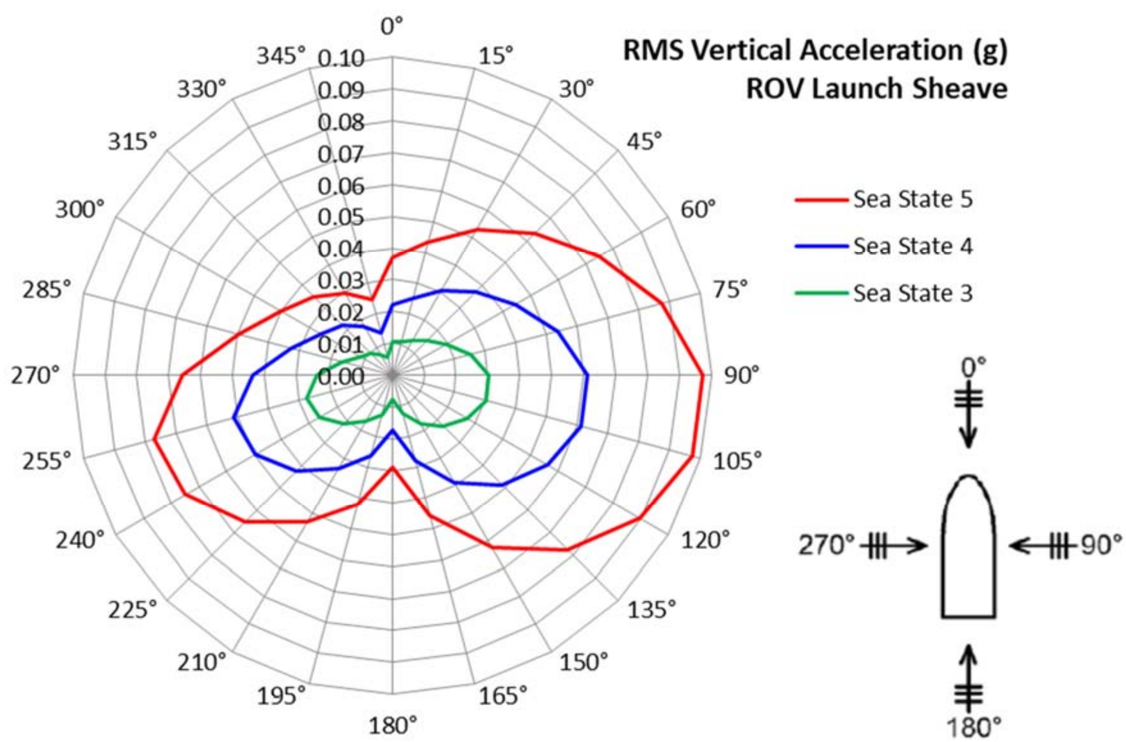


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at ROV Launch Sheave

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --

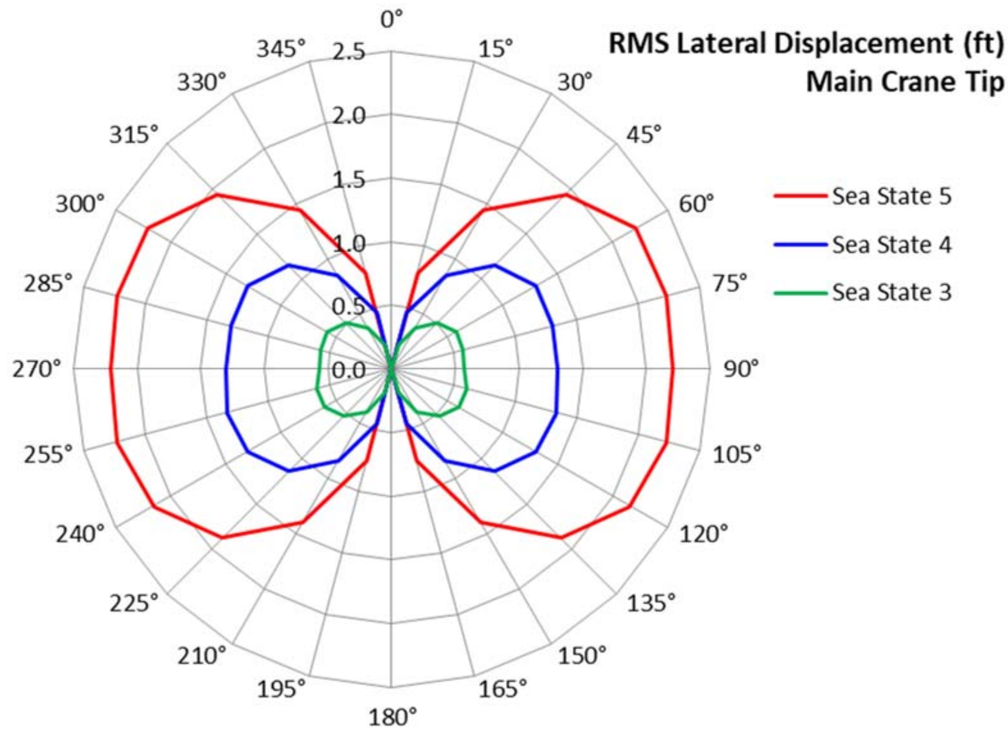


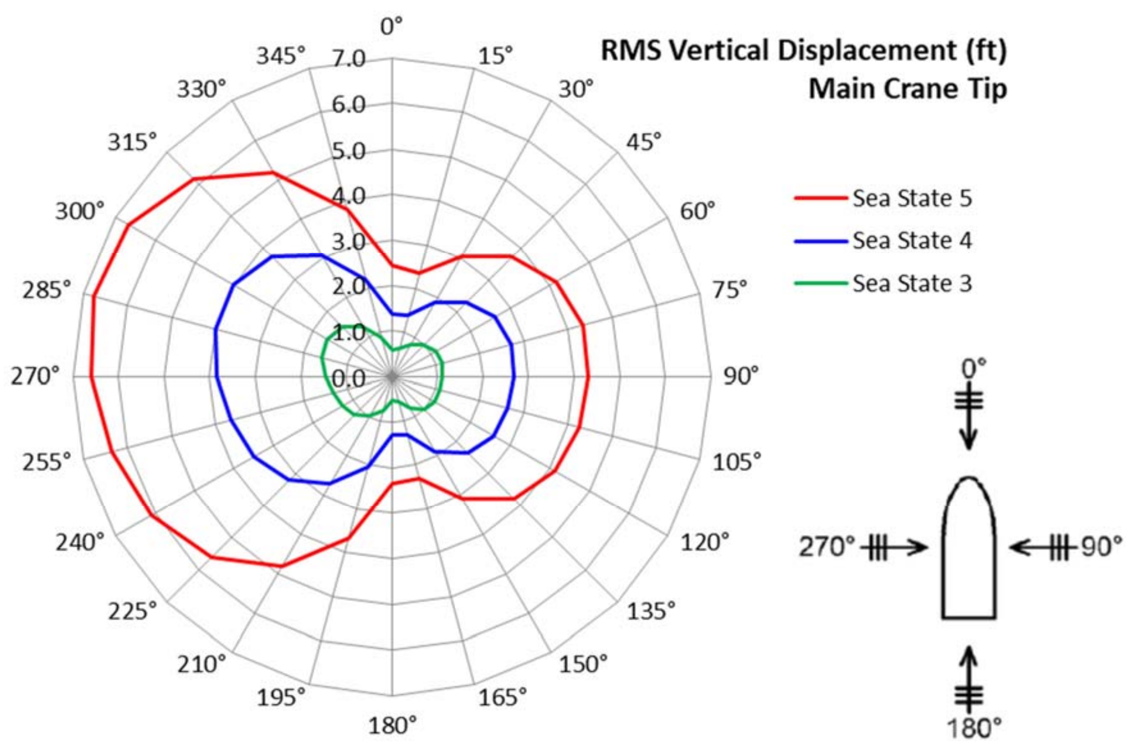


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Main Crane Tip

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --

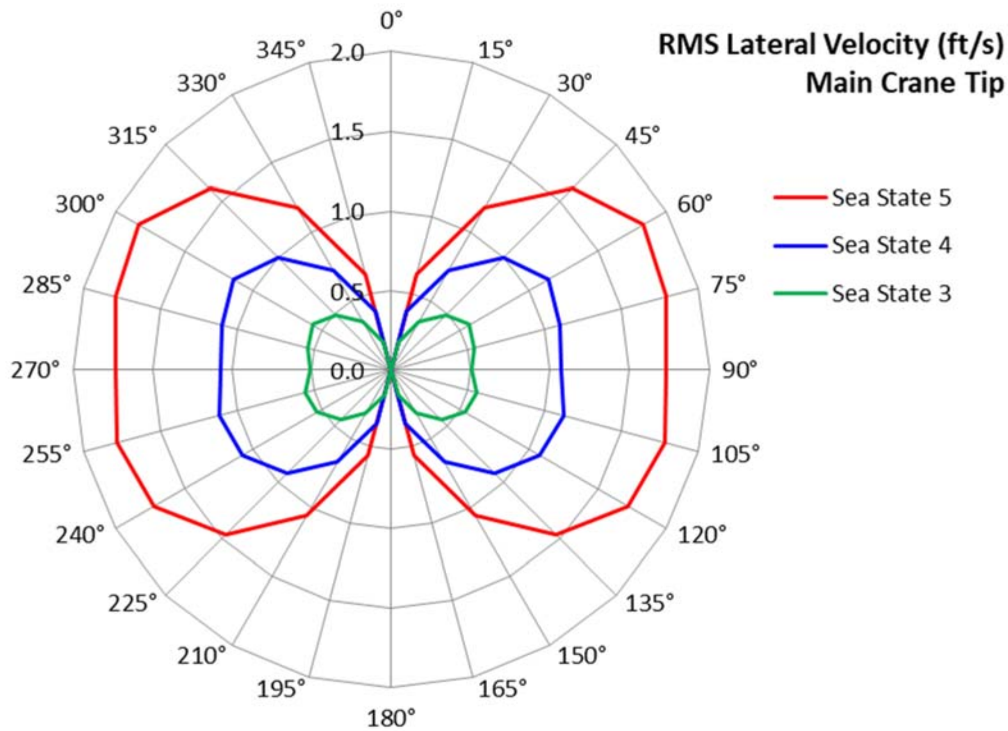


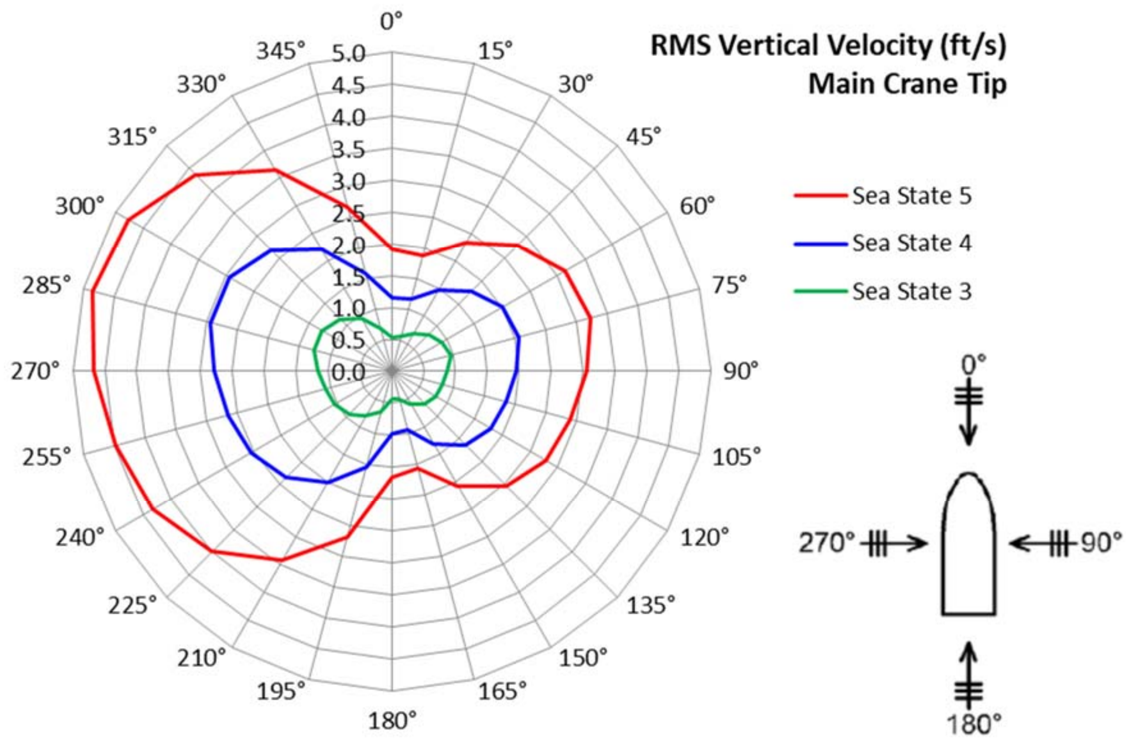


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Main Crane Tip

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --

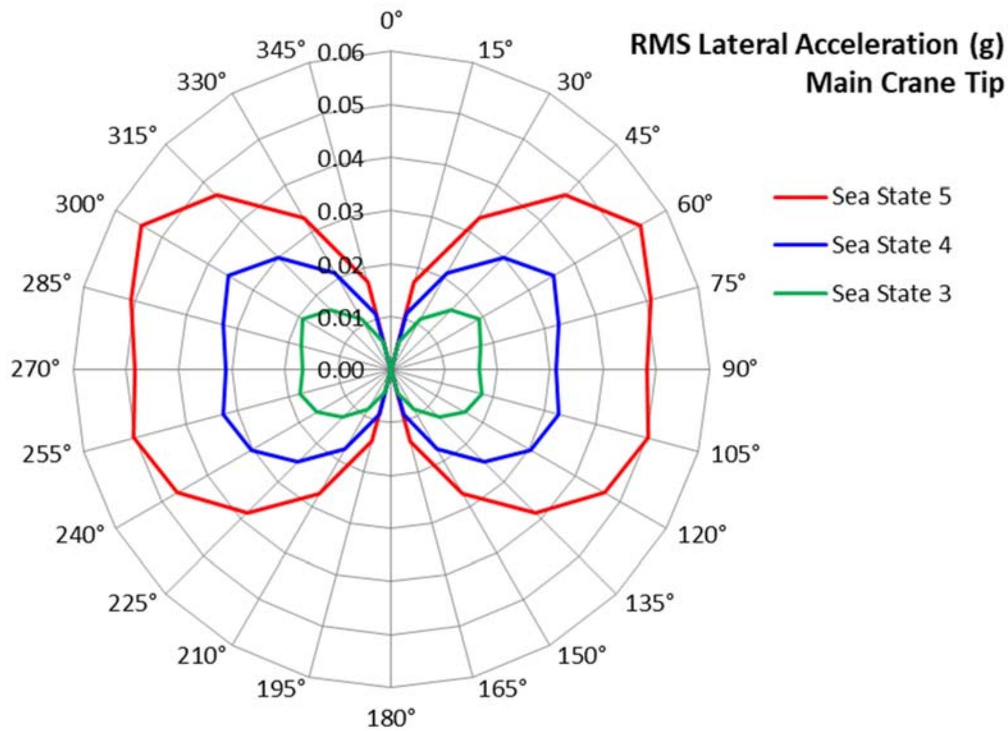


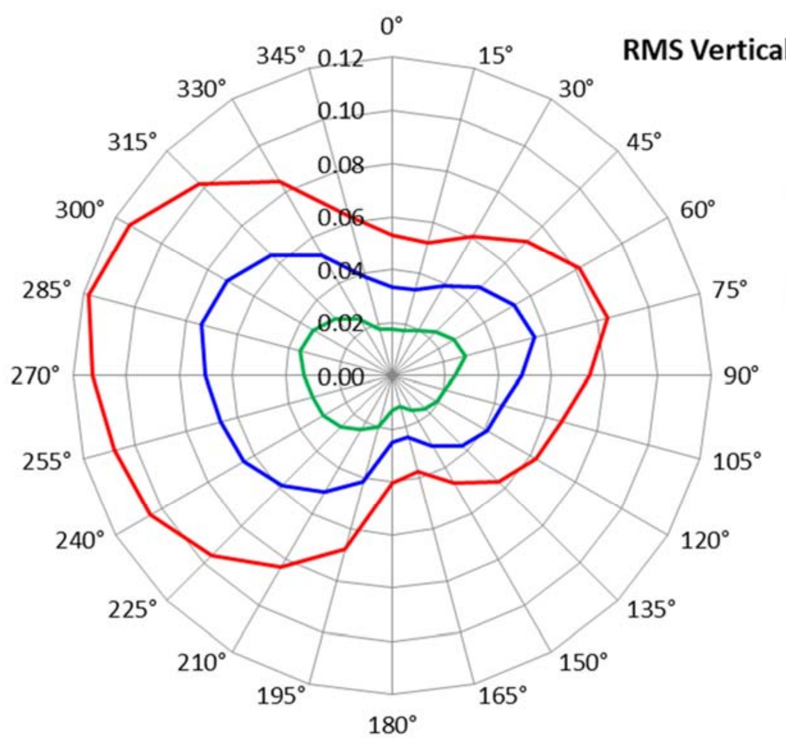


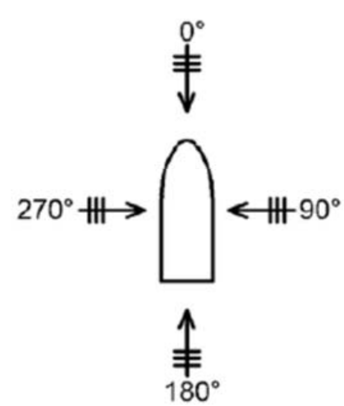
Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Main Crane Tip

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --



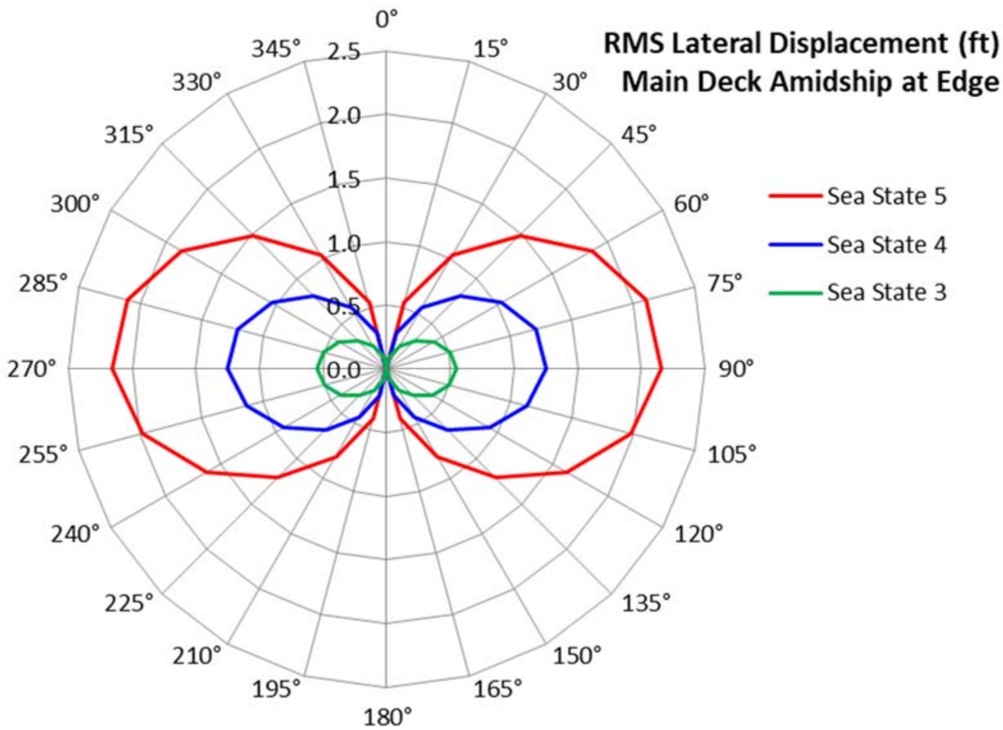


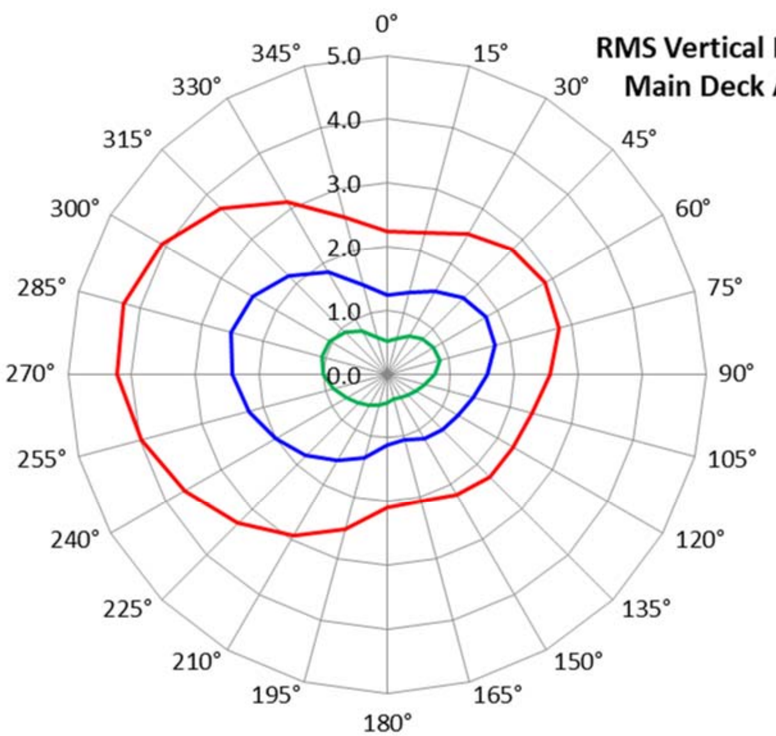


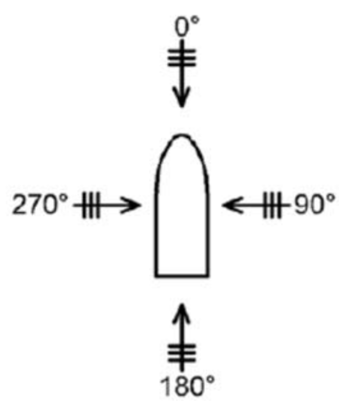
Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --



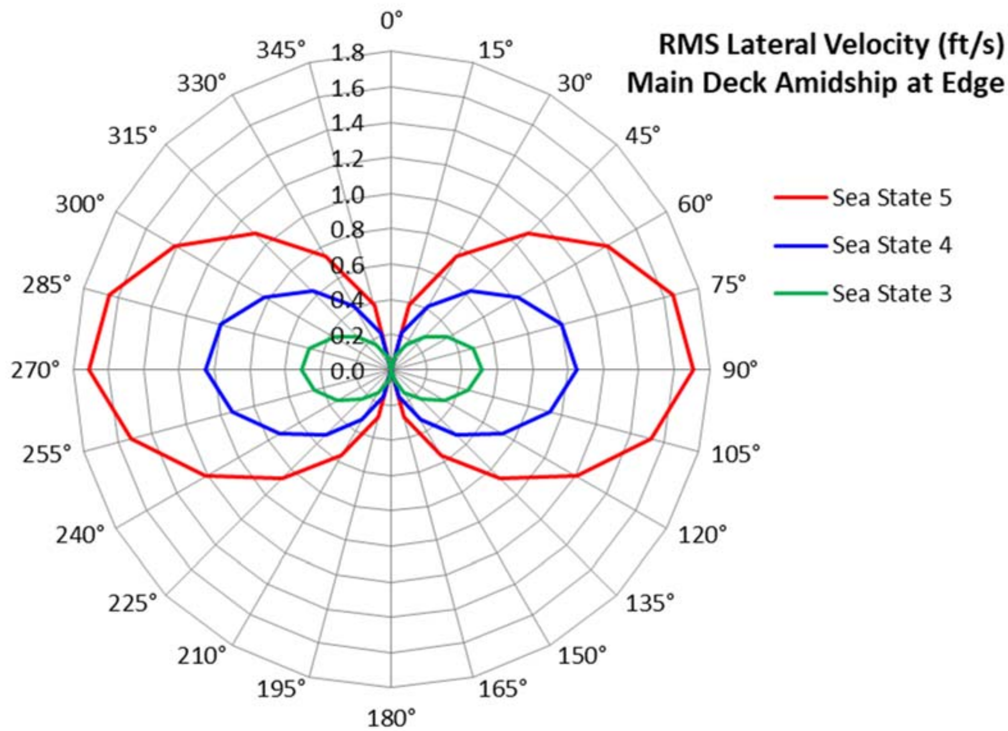


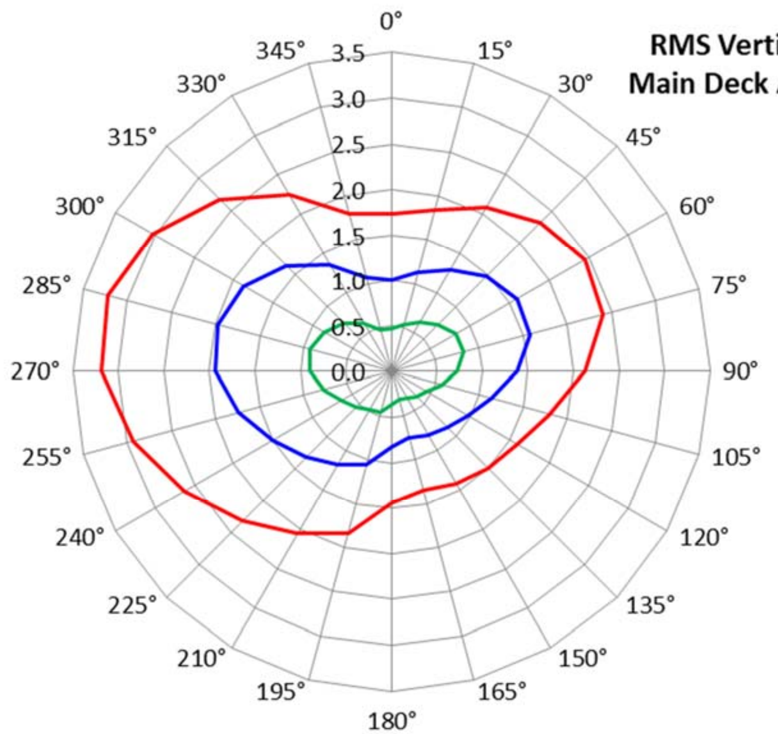


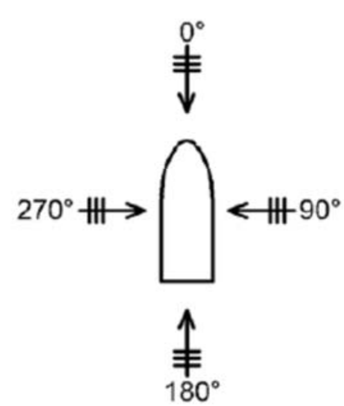
Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --



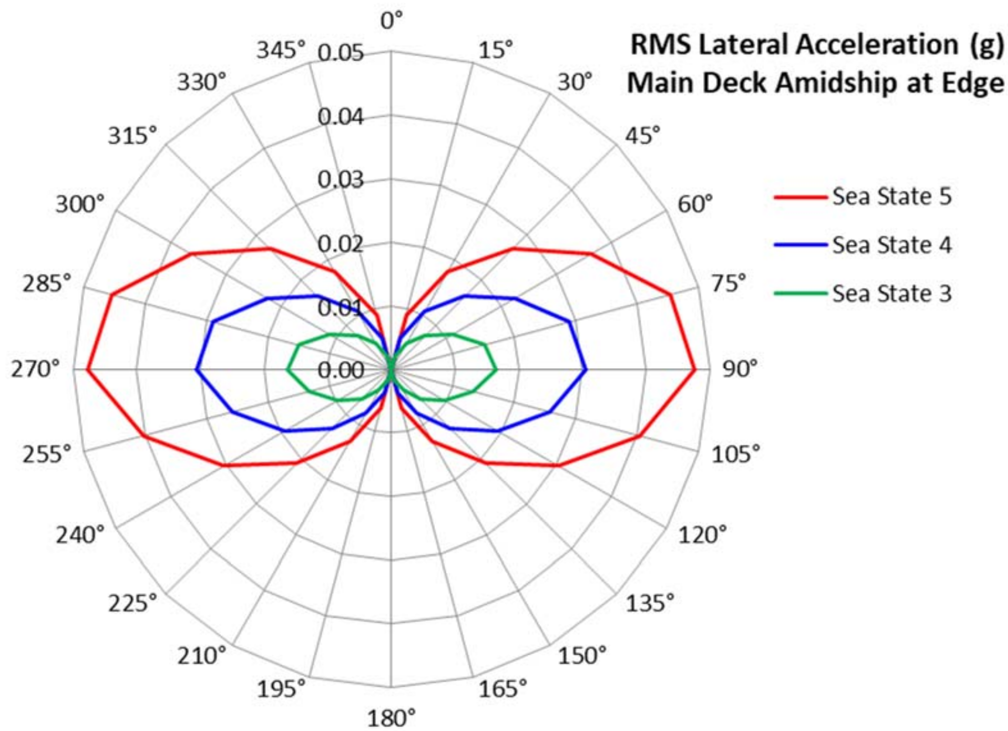


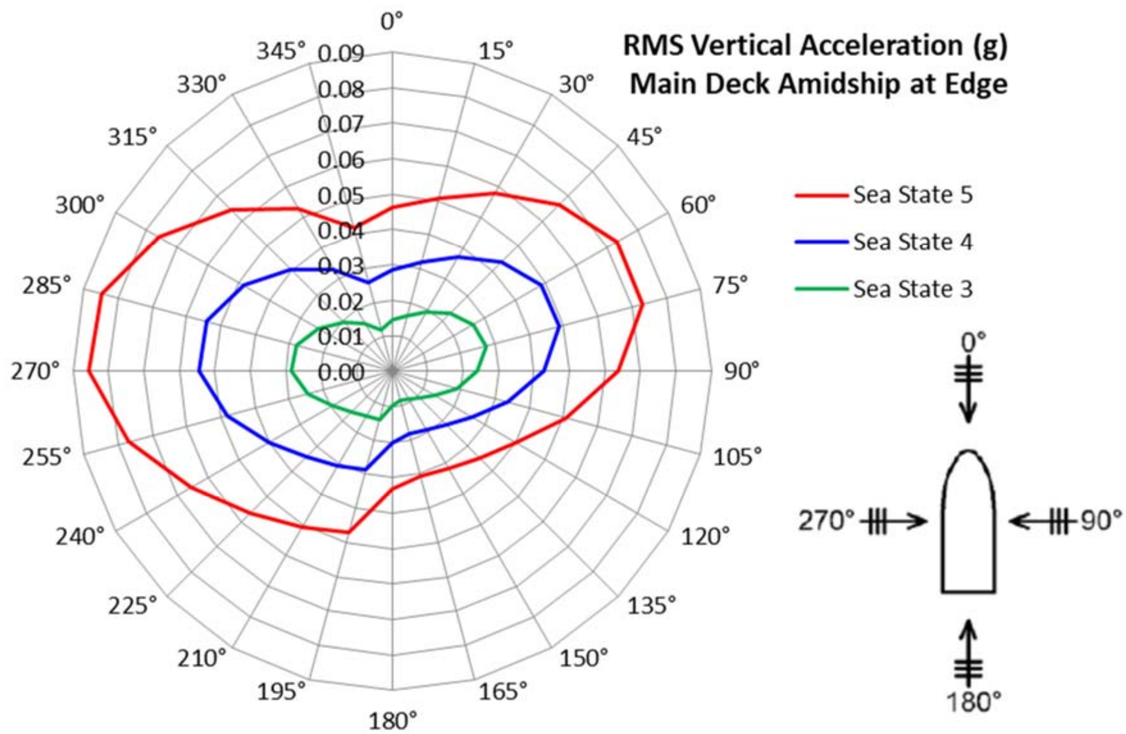


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --

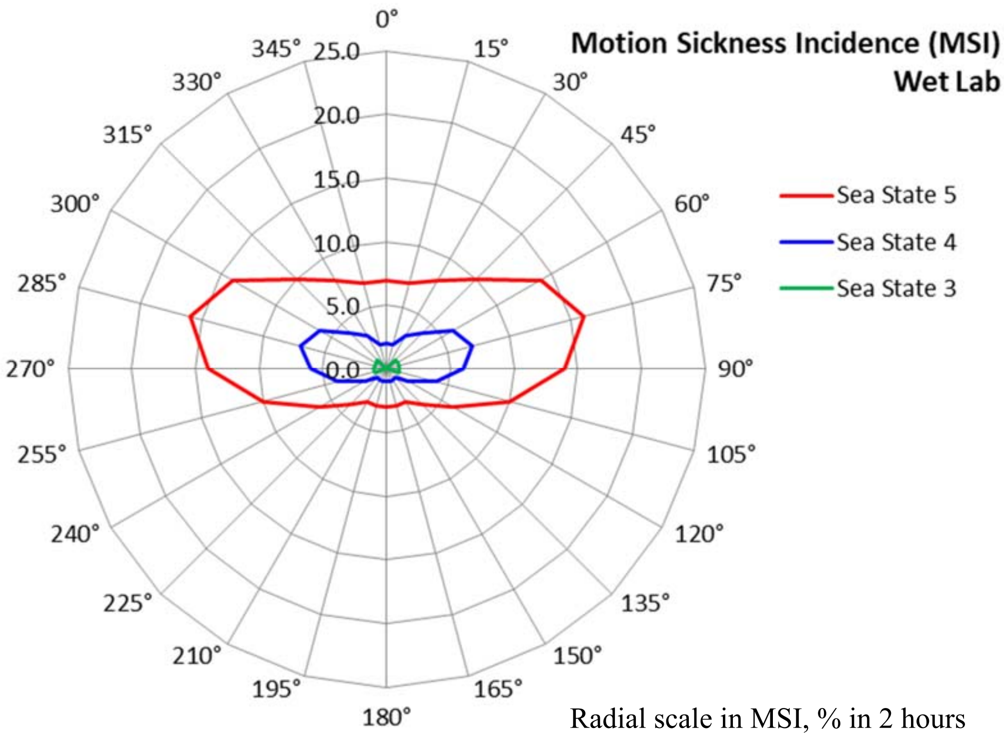




Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

Motion Sickness Incidence (MSI) in Wet Lab

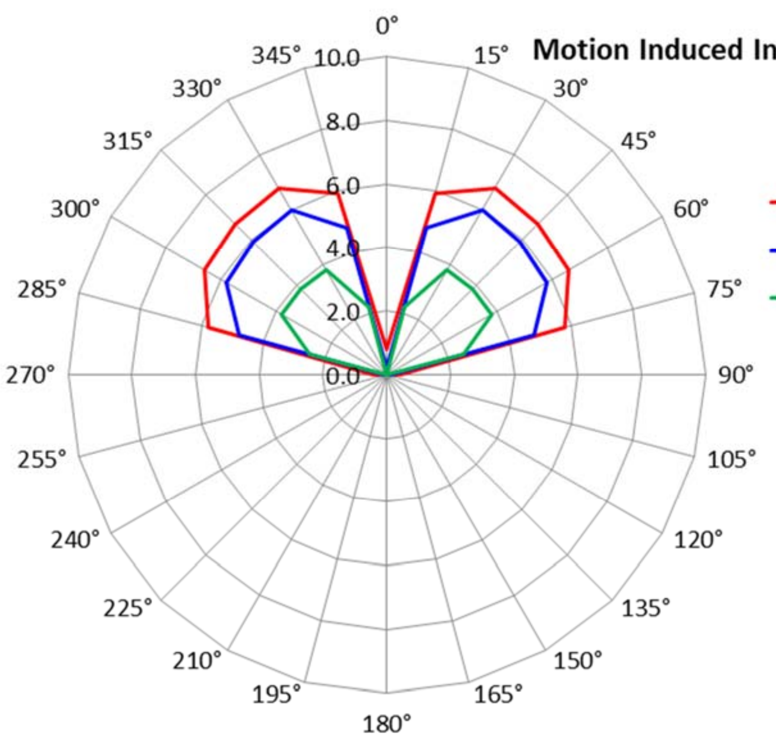
-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --

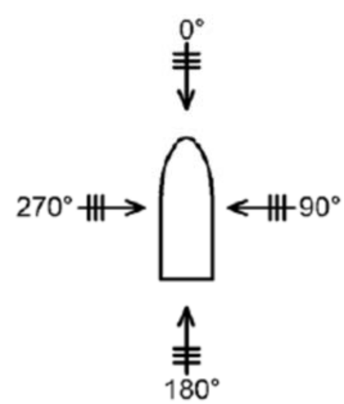


Radial scale in MSI, % in 2 hours
Circumferential scale in wave heading (deg)

Motion Induced Interruptions (MII) in Wet Lab

-- With Roll Stabilizers Turned Off and Full-length Bilge Keel --



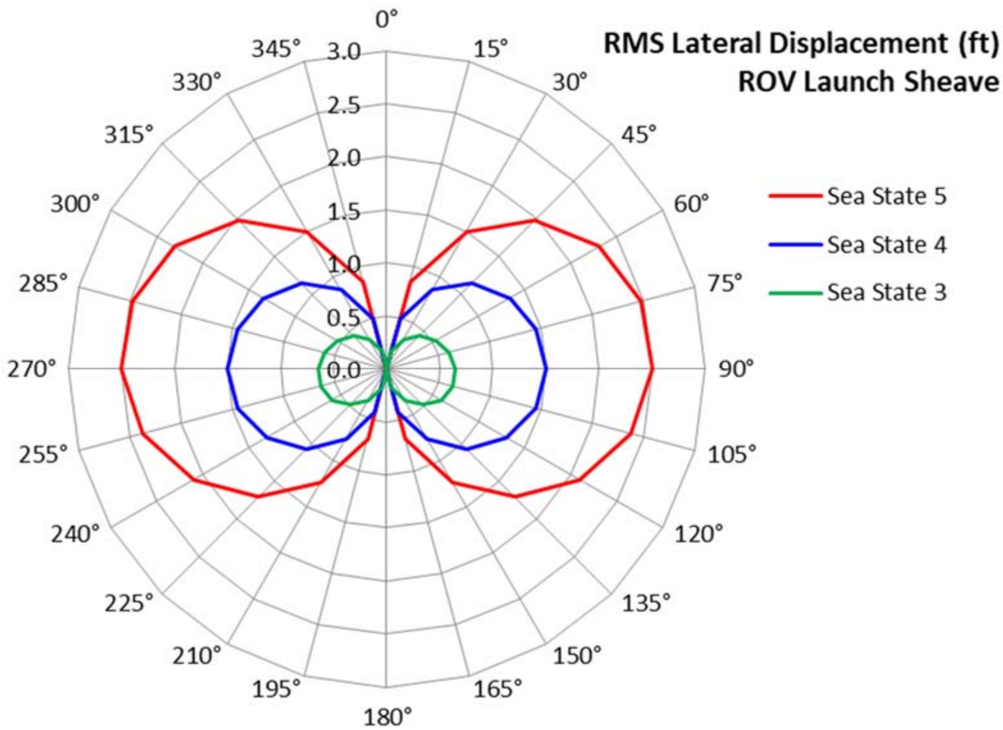


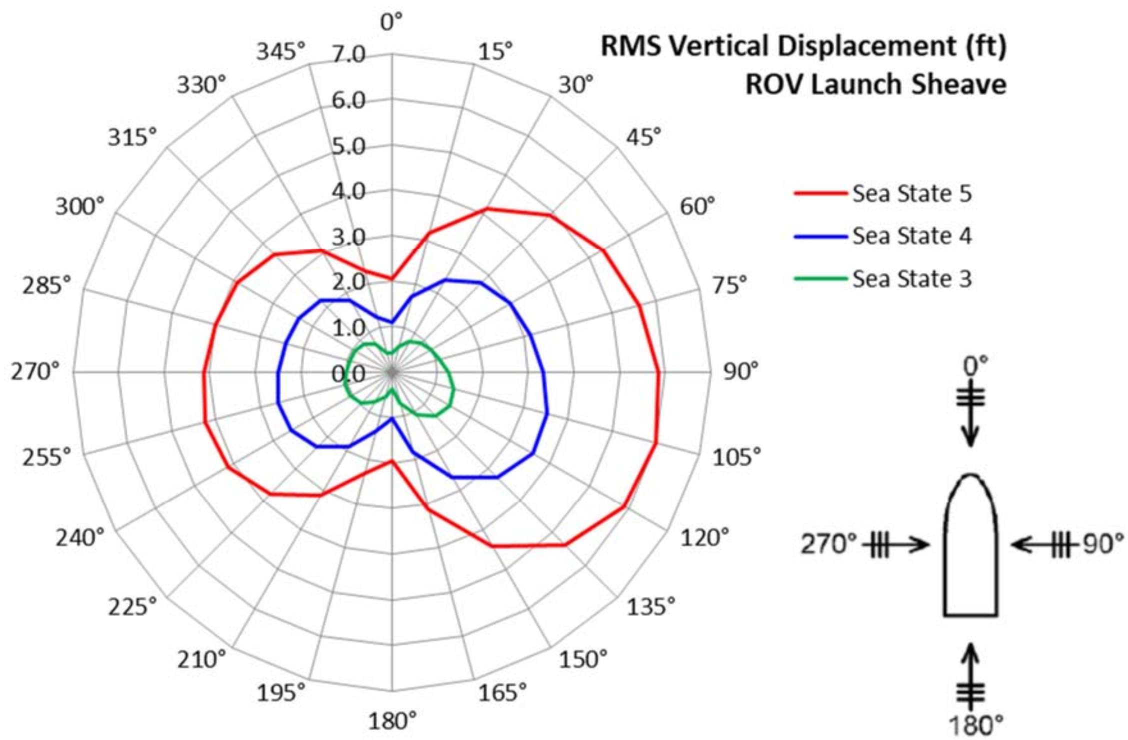
Radial scale in MII, occurrences per minute
Circumferential scale in wave heading (deg)

Appendix C Polar Diagrams – Vessel with Roll Stabilizers Turned Off and with Half-Length Bilge Keel

RMS Displacements at ROV Launch Sheave

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --

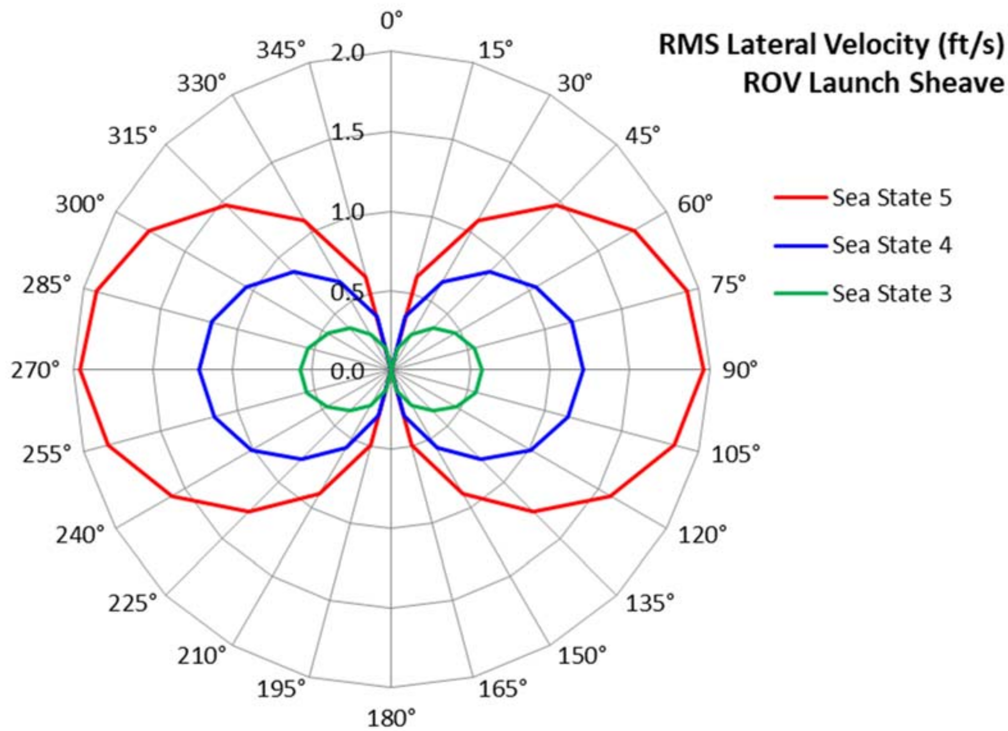


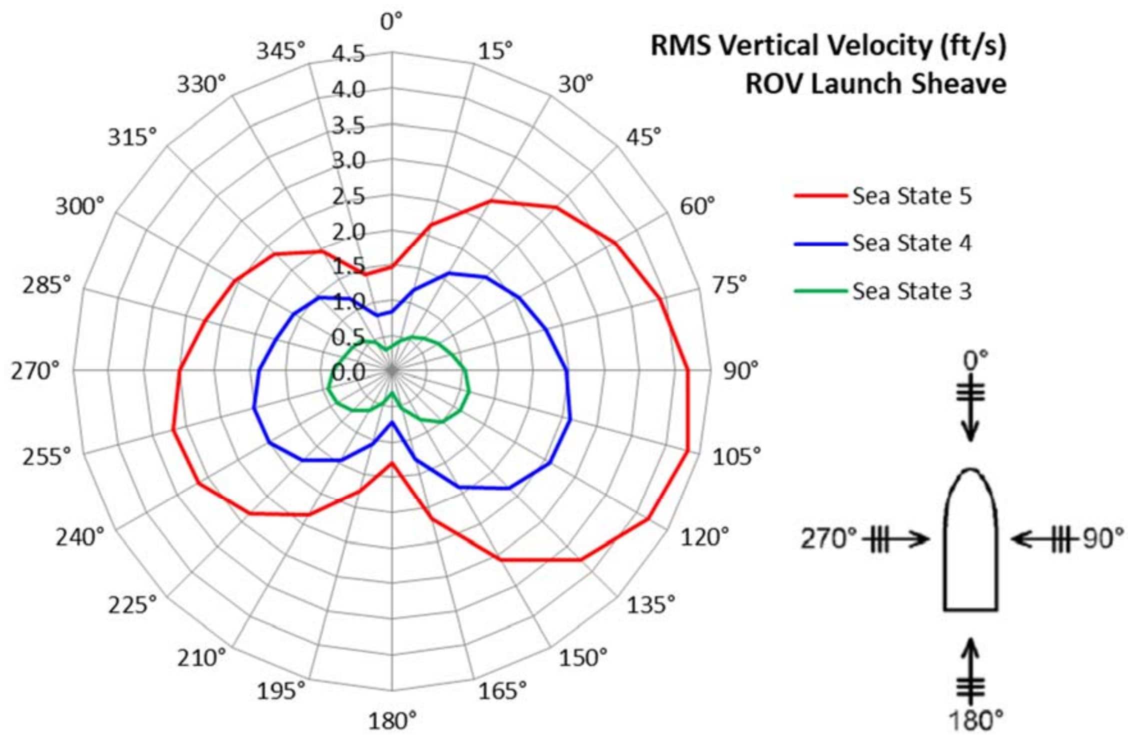


Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at ROV Launch Sheave

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --

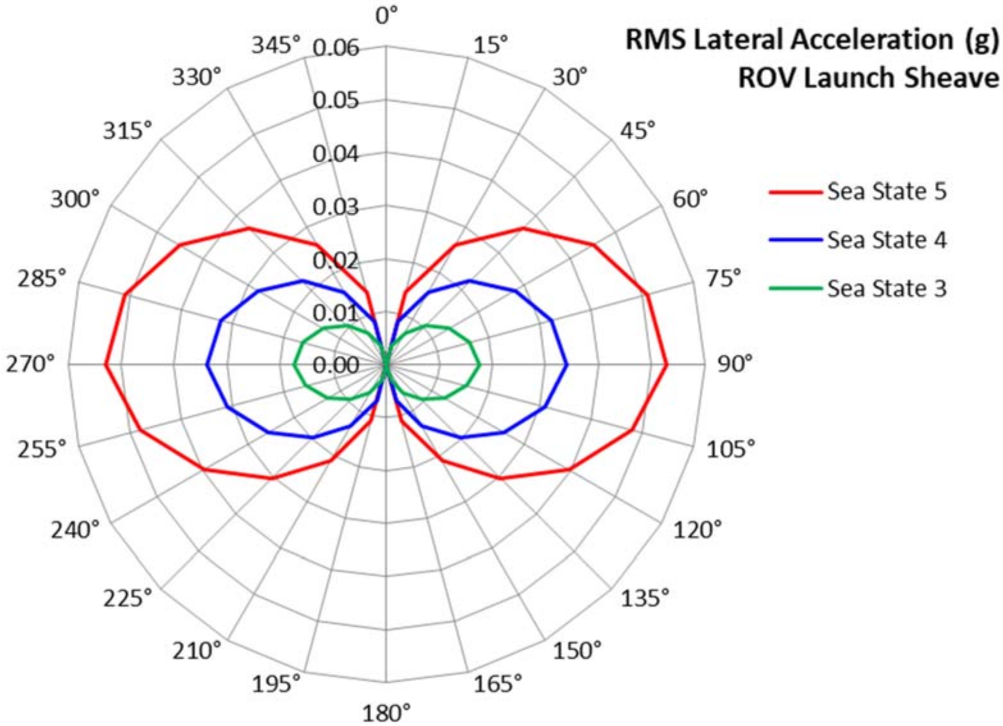


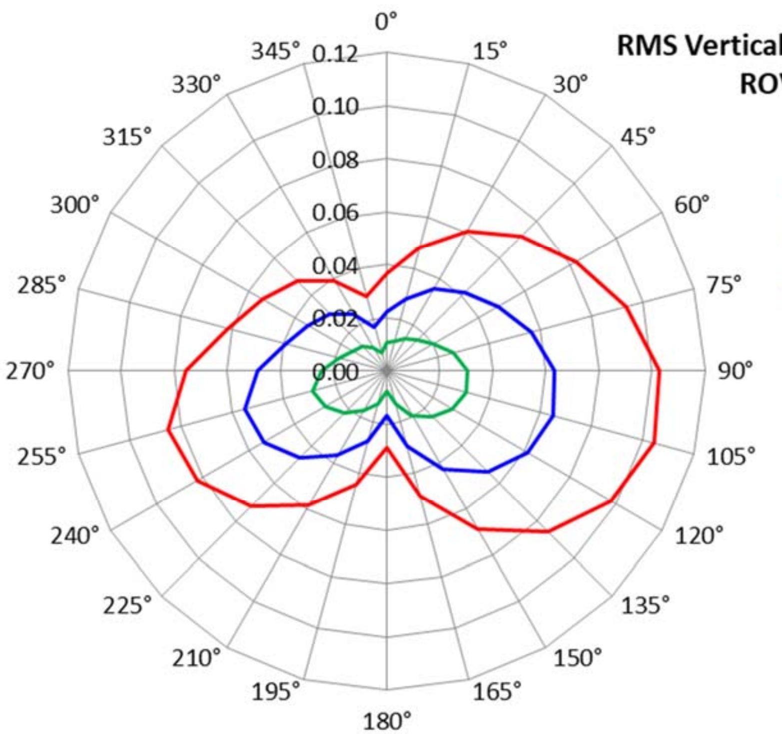


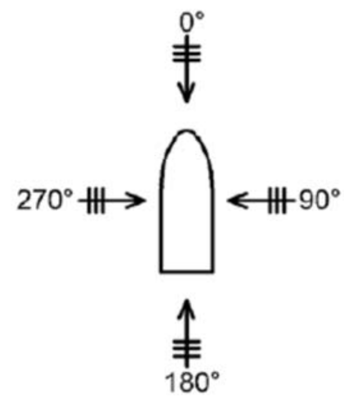
Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at ROV Launch Sheave

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --



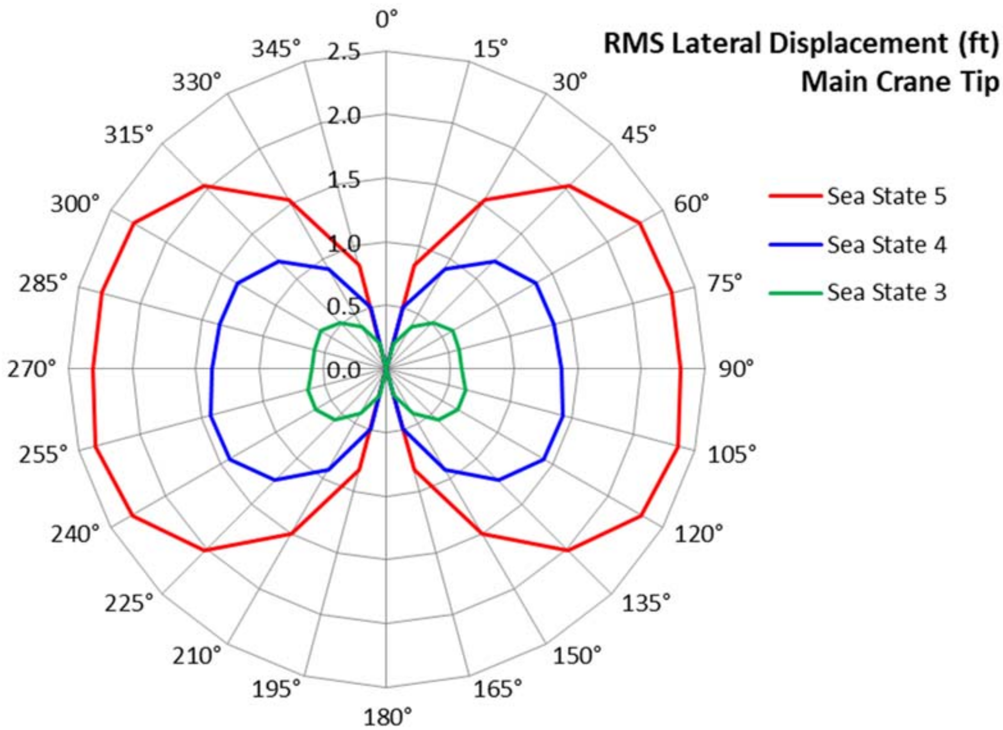


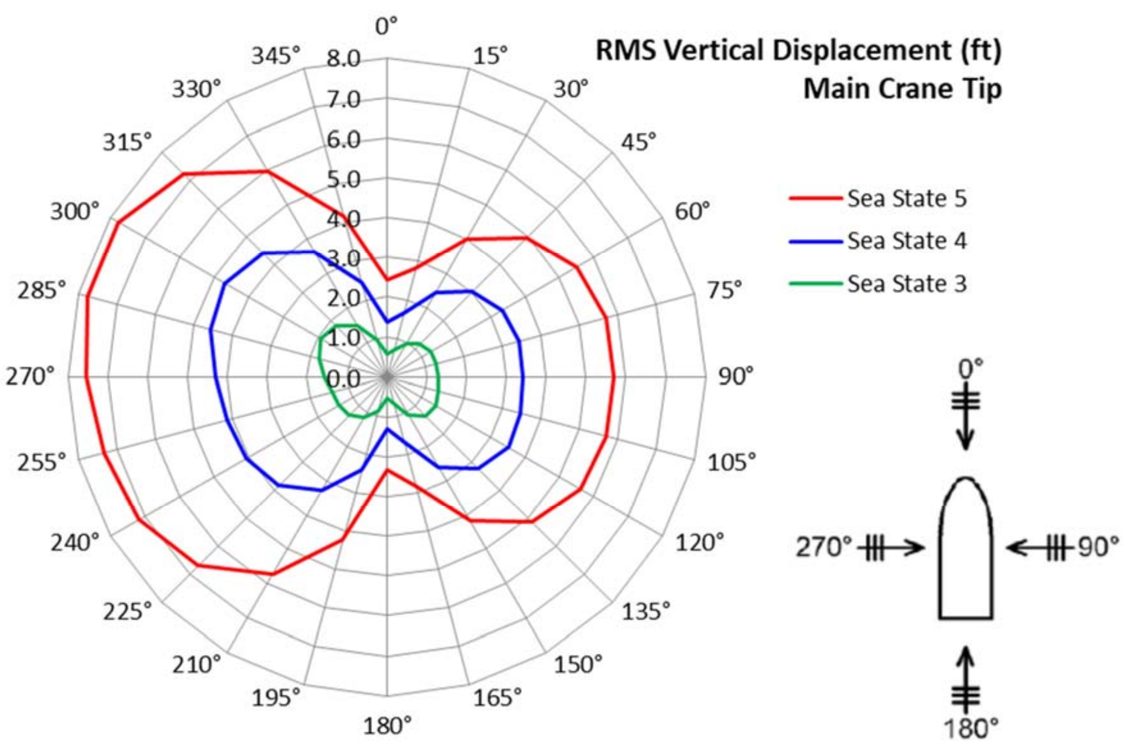


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Main Crane Tip

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --

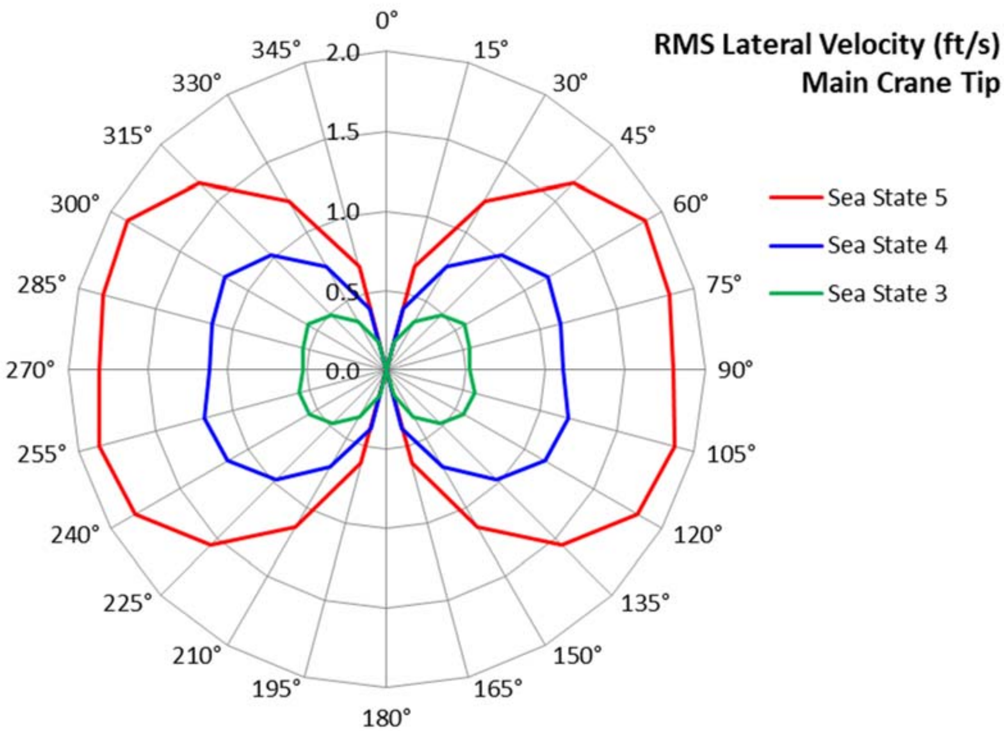


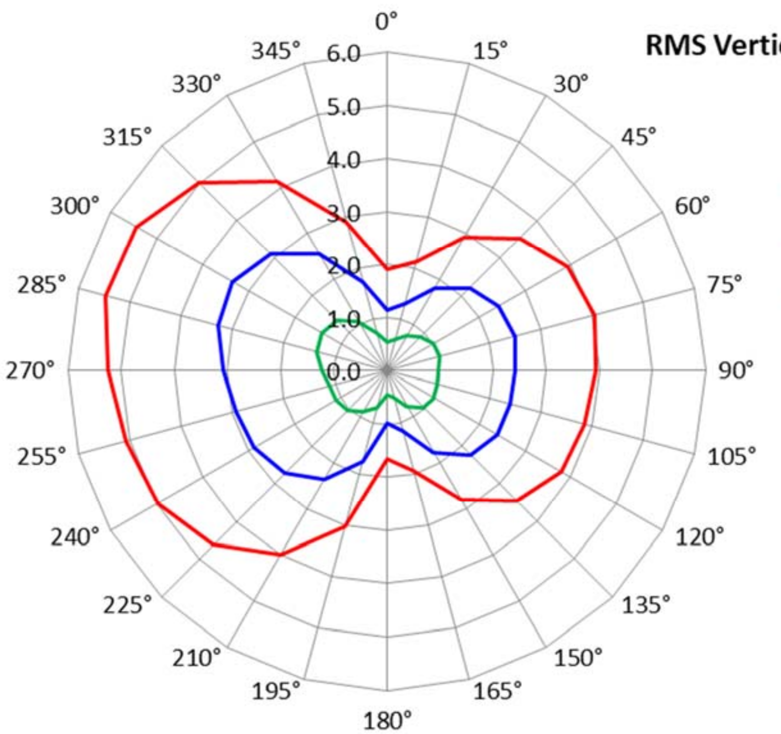


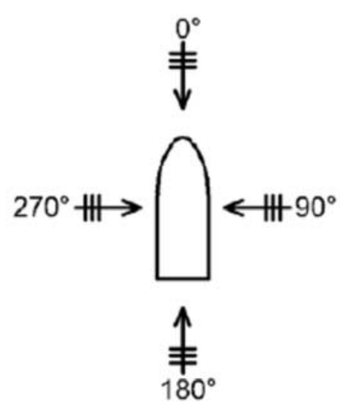
Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Main Crane Tip

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --



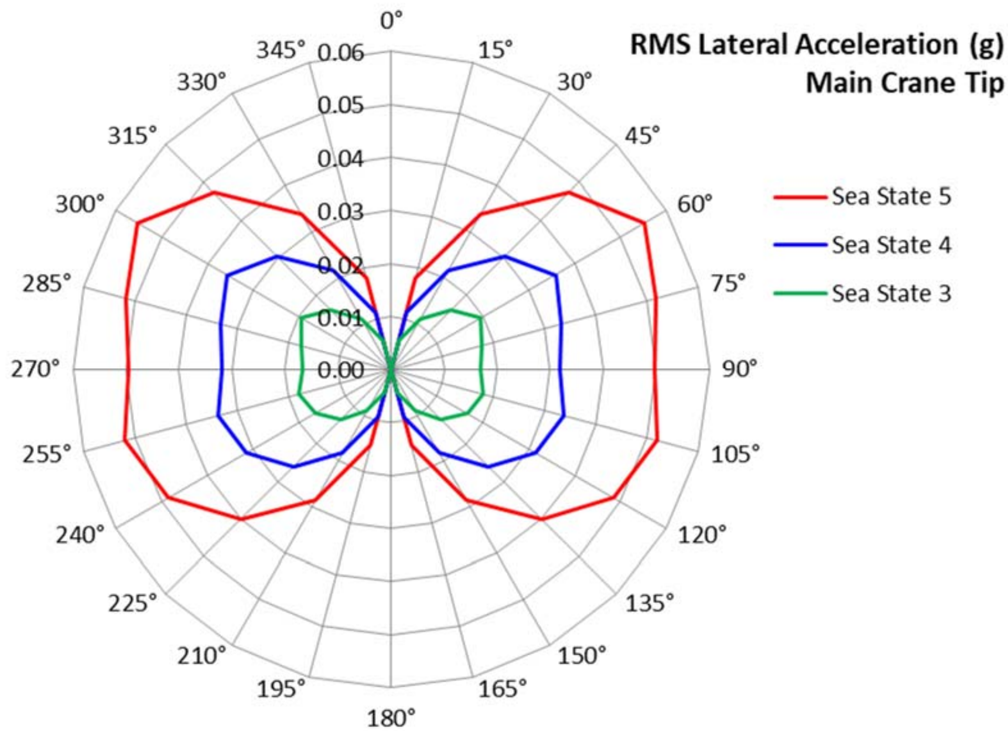


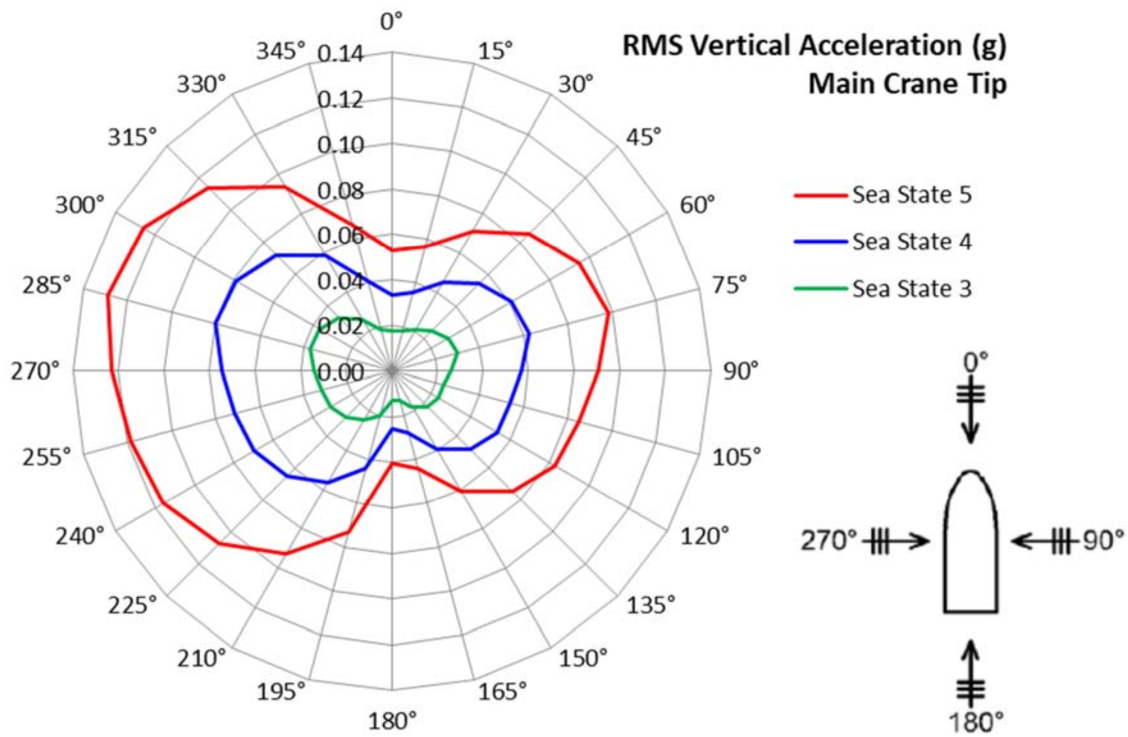


Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Main Crane Tip

-- With Roll Stabilizers <u>Turned Off</u> and <u>Half-length</u> Bilge Keel --

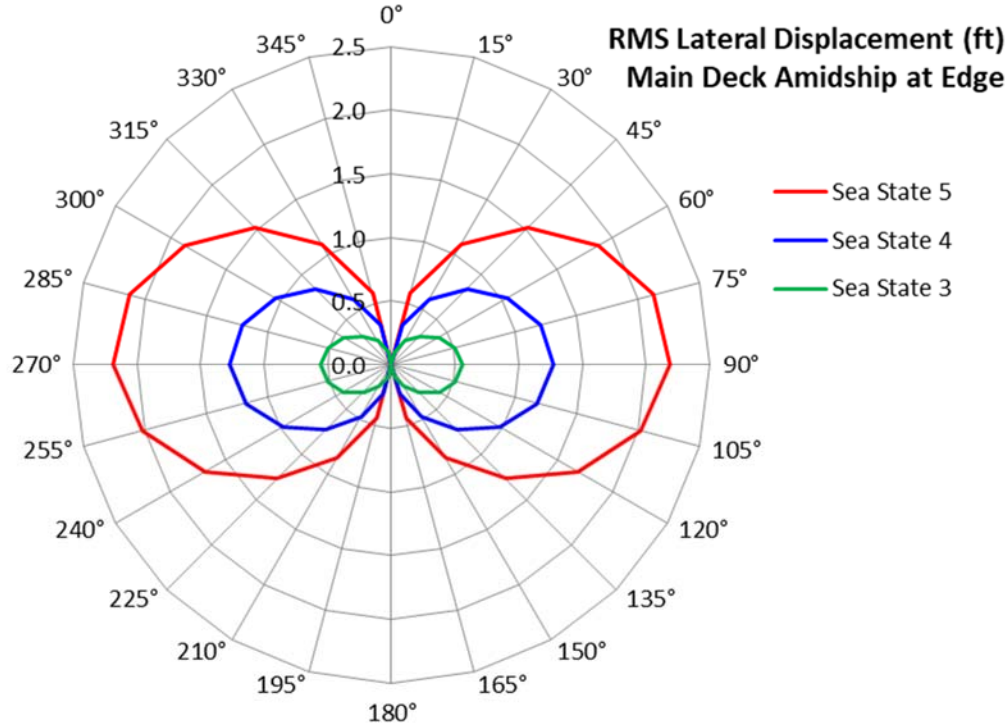


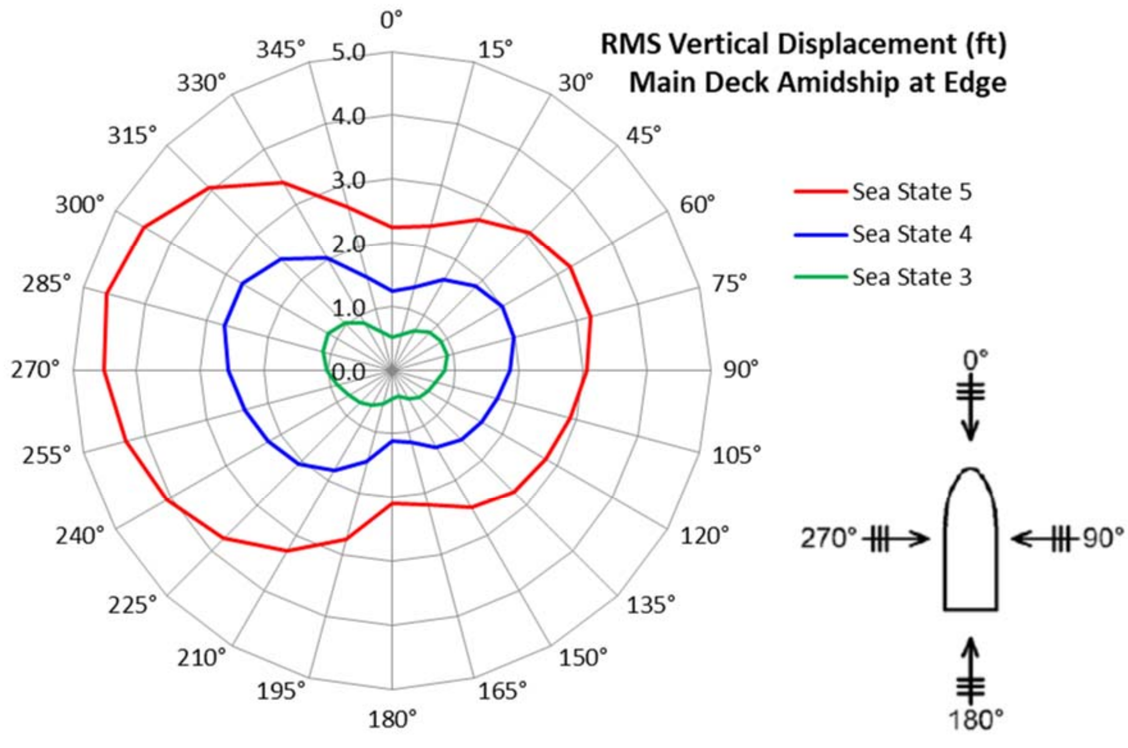


Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

RMS Displacements at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --

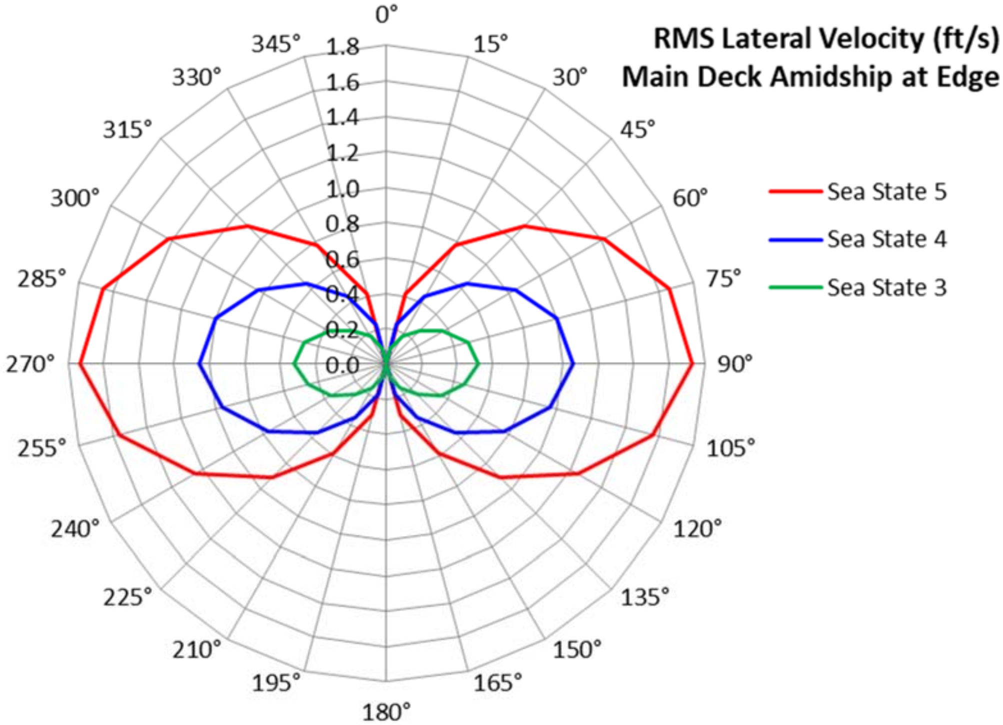


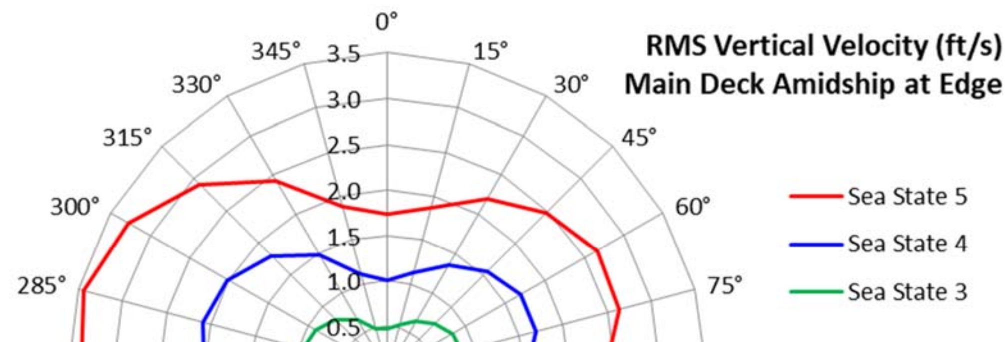


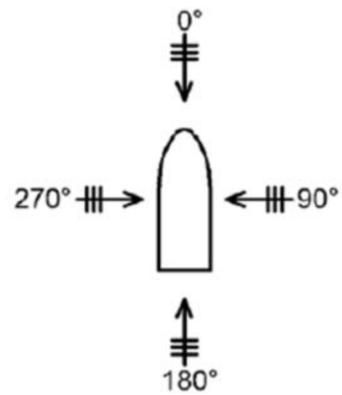
Radial scale in RMS displacement (ft)
Circumferential scale in wave heading (deg)

RMS Velocities at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --



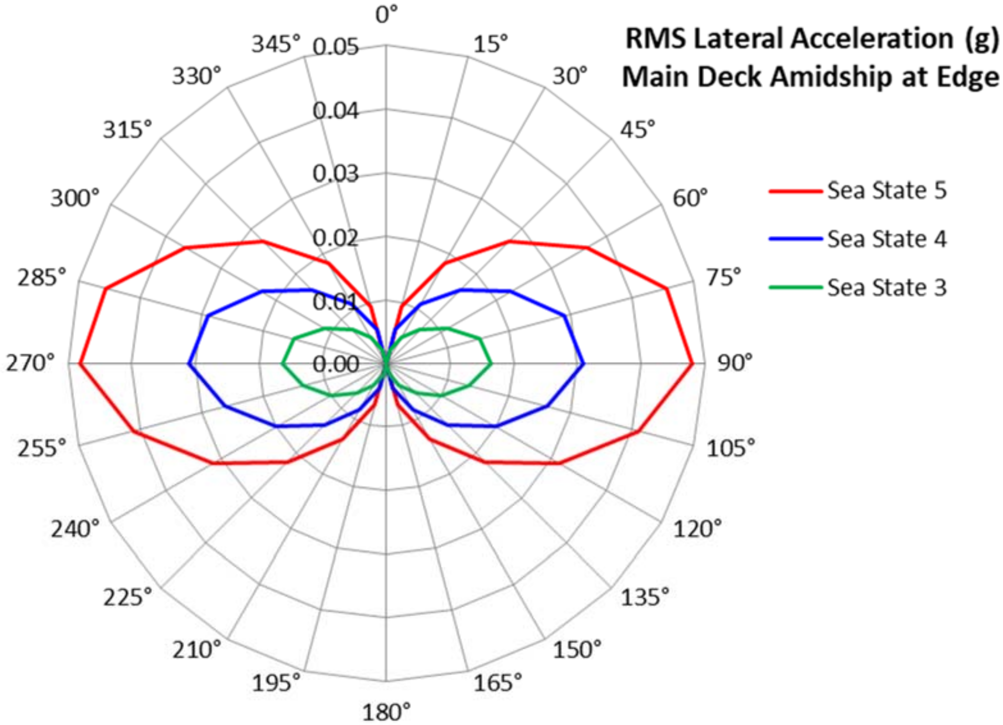


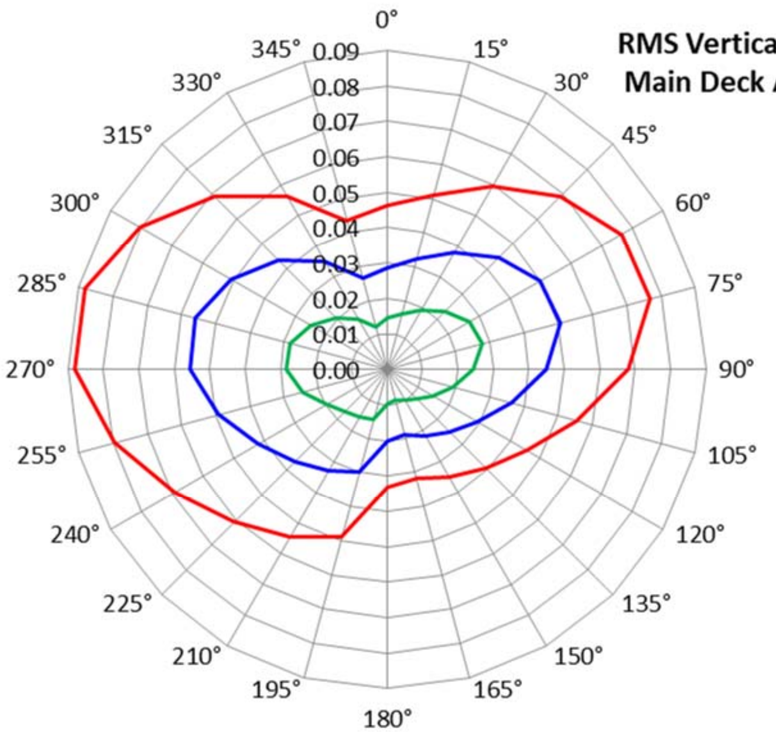


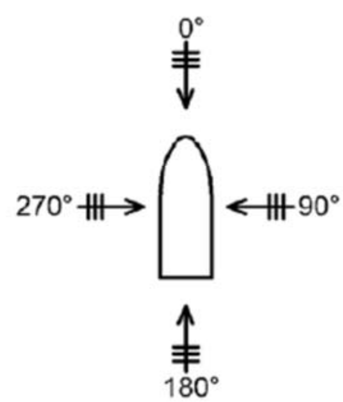
Radial scale in RMS velocity (ft/s)
Circumferential scale in wave heading (deg)

RMS Accelerations at Main Deck Amidship at Deck Edge

-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --



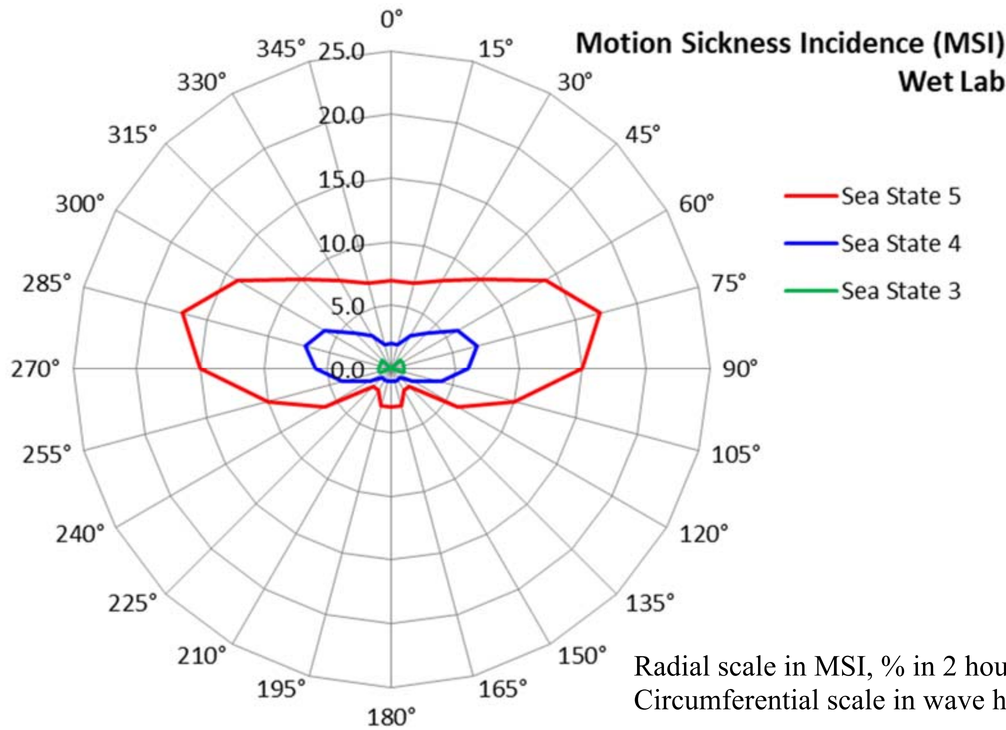




Radial scale in RMS acceleration (g)
Circumferential scale in wave heading (deg)

Motion Sickness Incidence (MSI) in Wet Lab

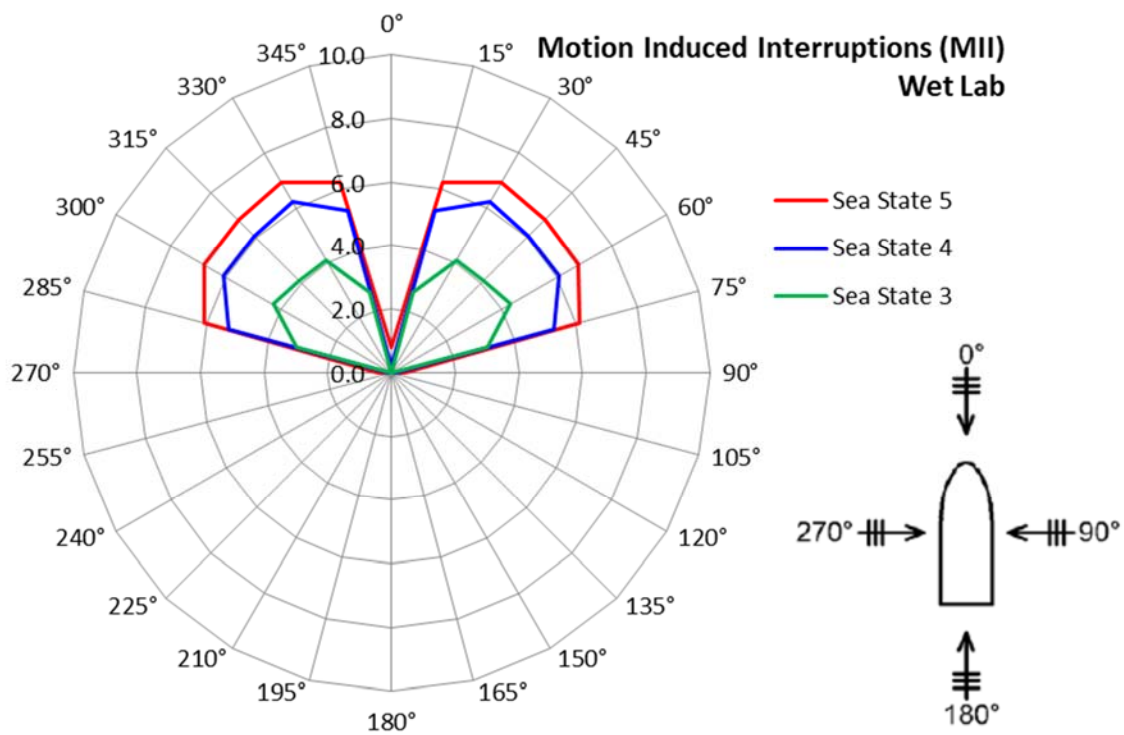
-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --



Radial scale in MSI, % in 2 hours
Circumferential scale in wave heading (deg)

Motion Induced Interruptions (MII) in Wet Lab

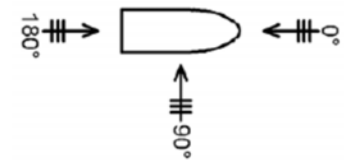
-- With Roll Stabilizers Turned Off and Half-length Bilge Keel --

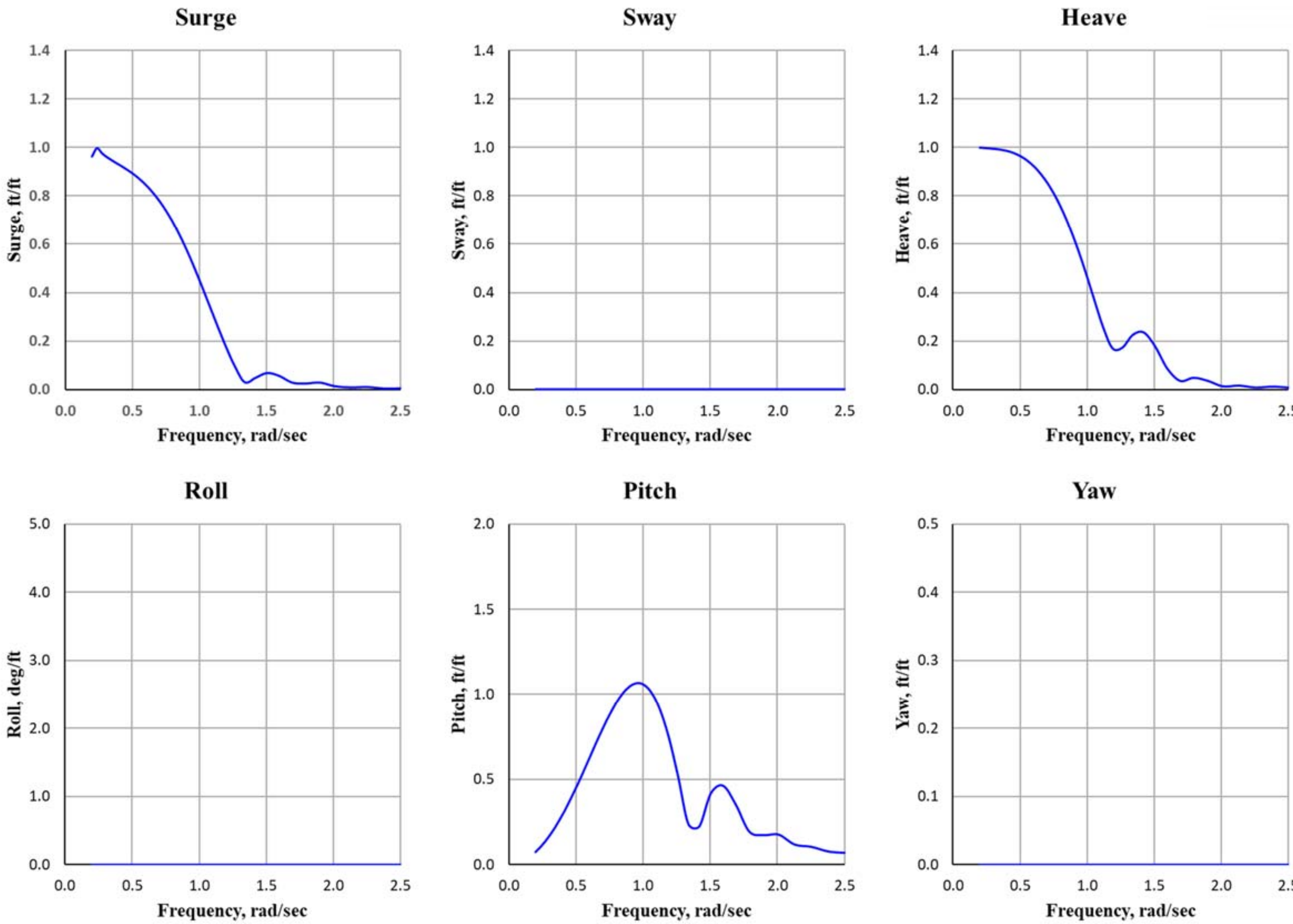


Radial scale in MII, occurrences per minute
Circumferential scale in wave heading (deg)

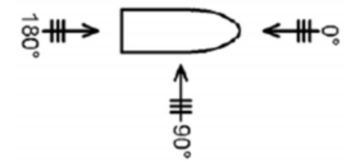
Appendix D Response Amplitude Operators – Vessel with Roll Stabilizers Turned On and with Full-Length Bilge Keel

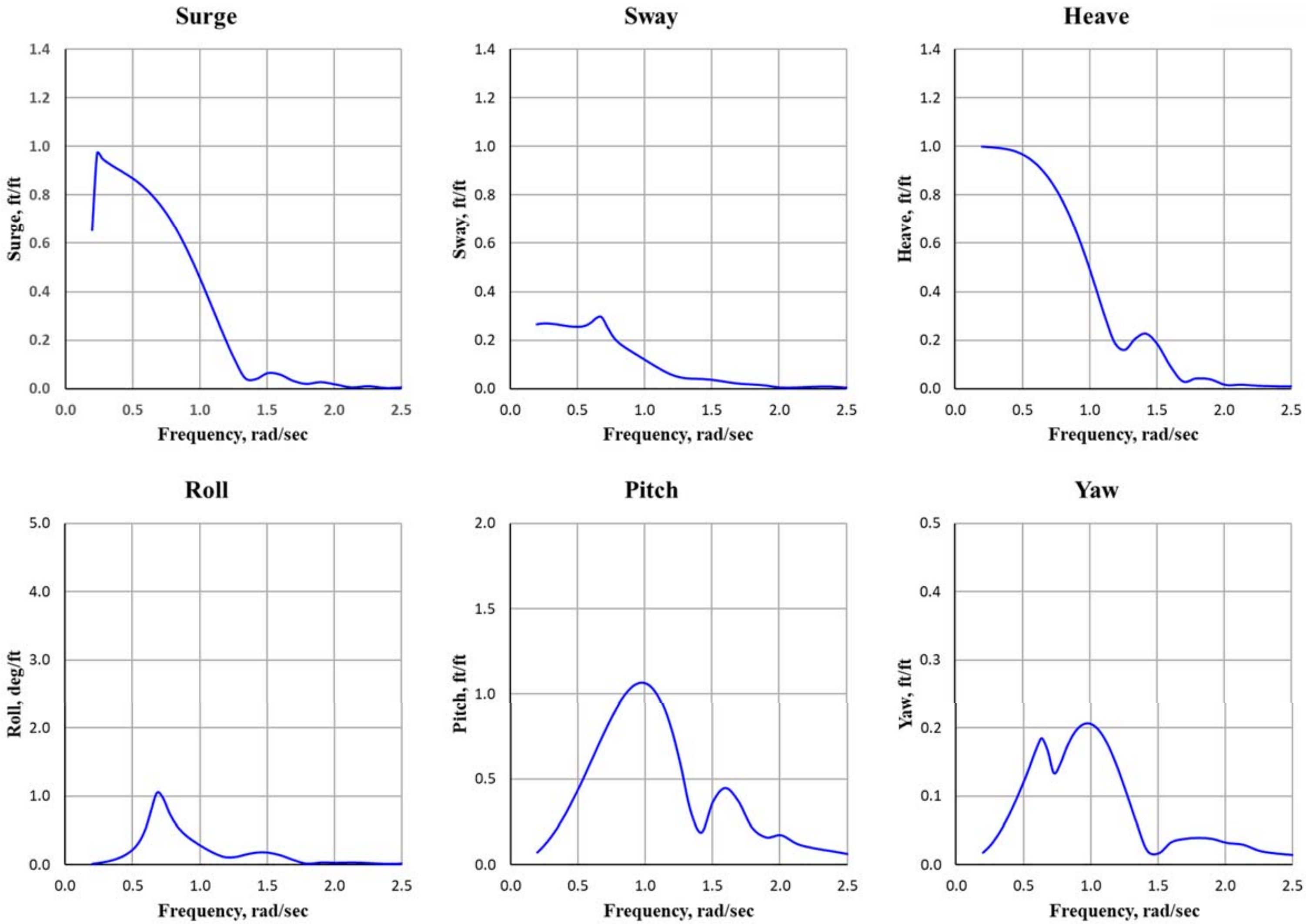
Magnitude of Response Amplitude Operators at Heading = 180 deg



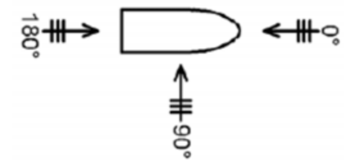


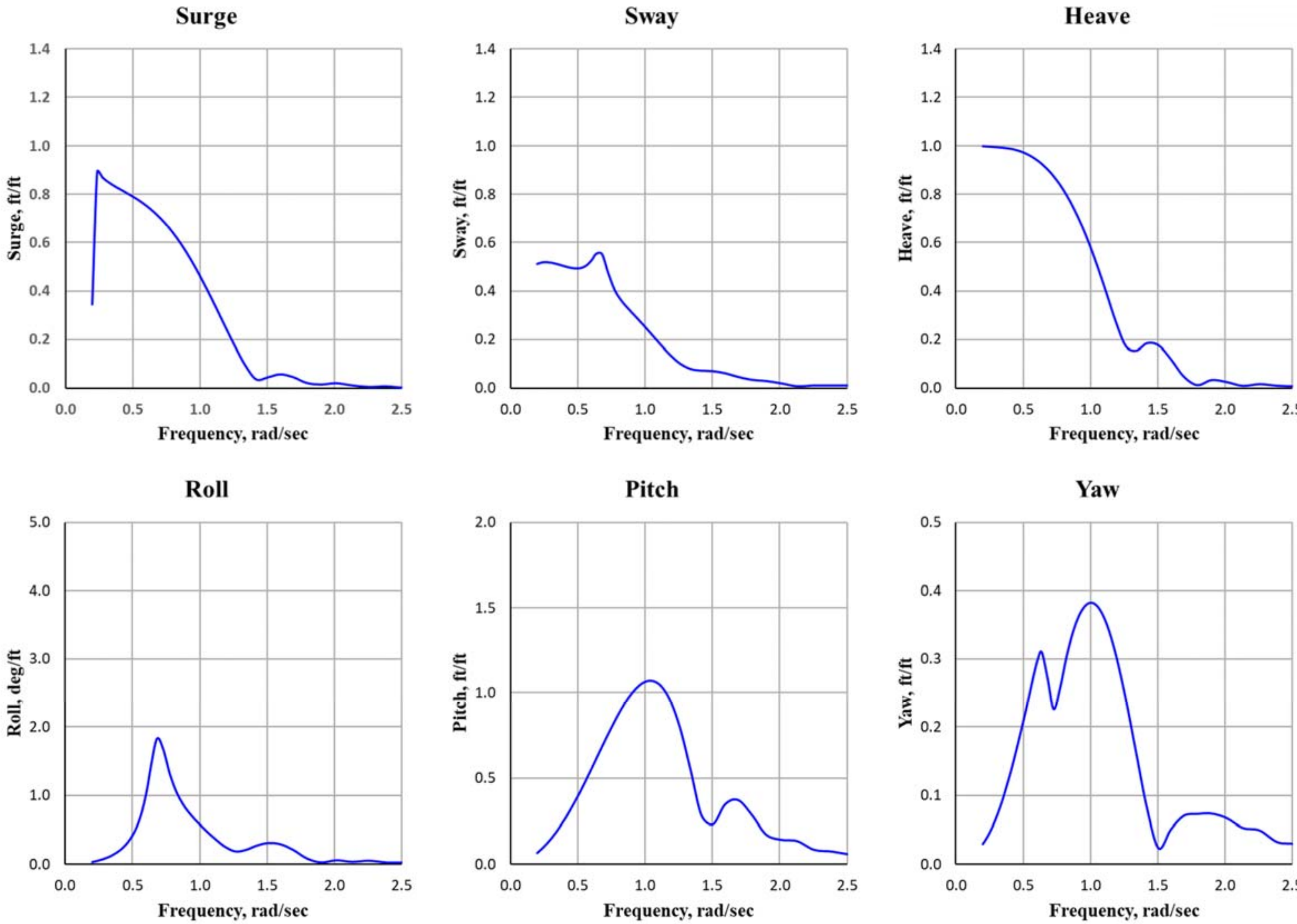
Magnitude of Response Amplitude Operators at Heading = 165 deg



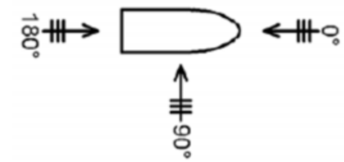


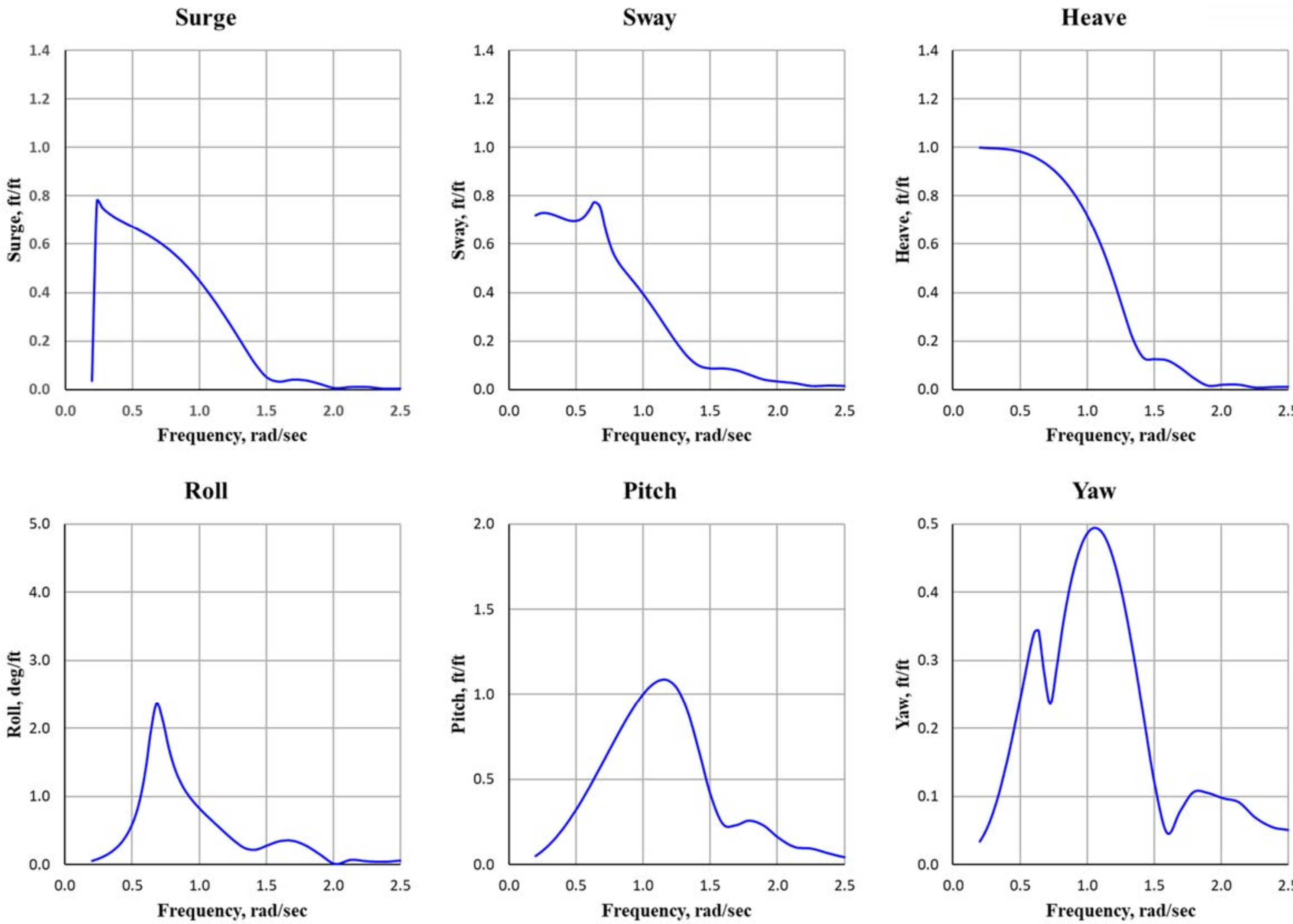
Magnitude of Response Amplitude Operators at Heading = 150 deg



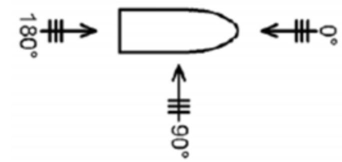


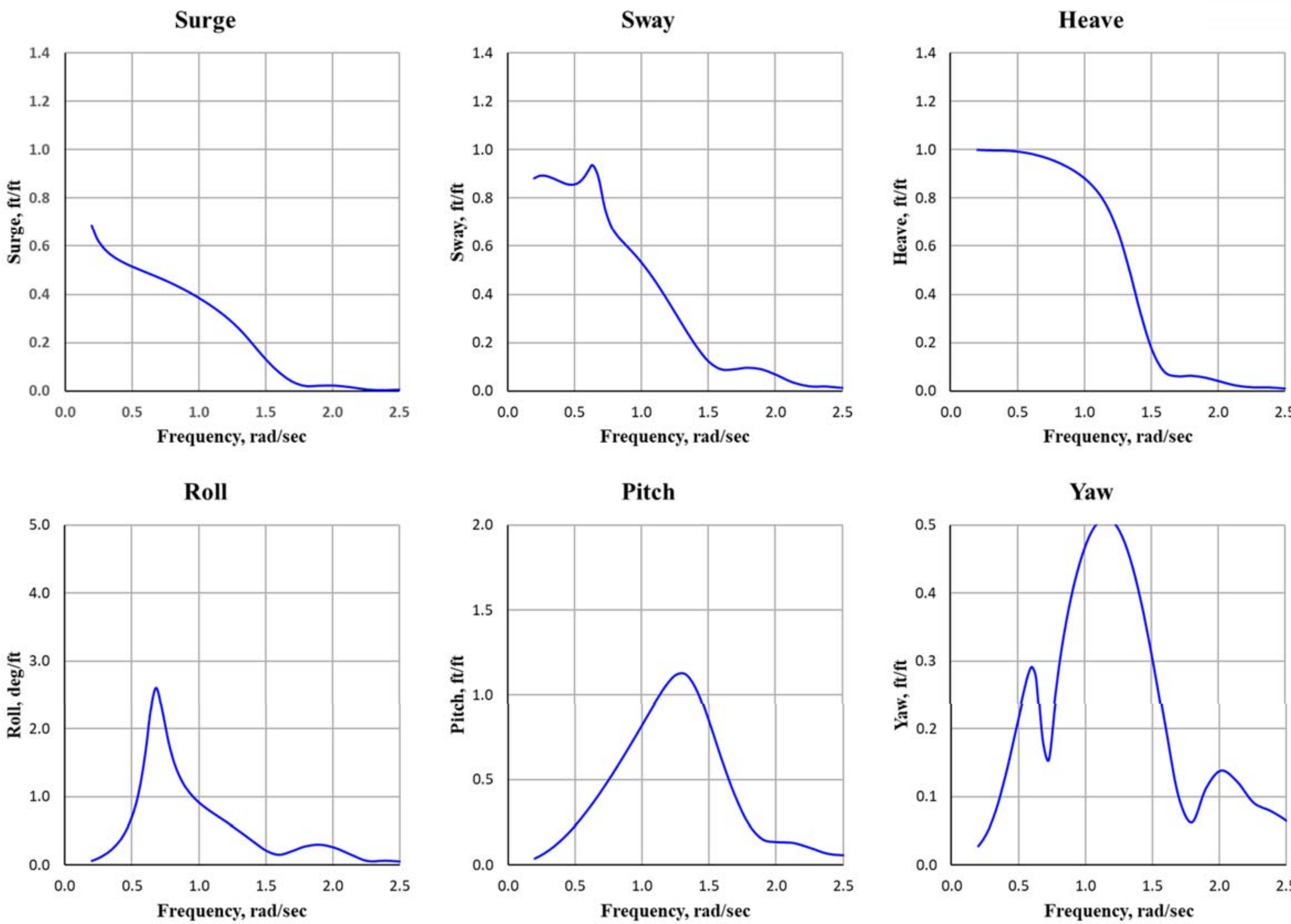
Magnitude of Response Amplitude Operators at Heading = 135 deg



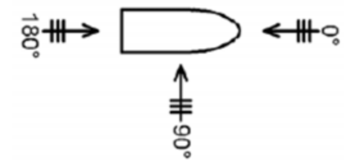


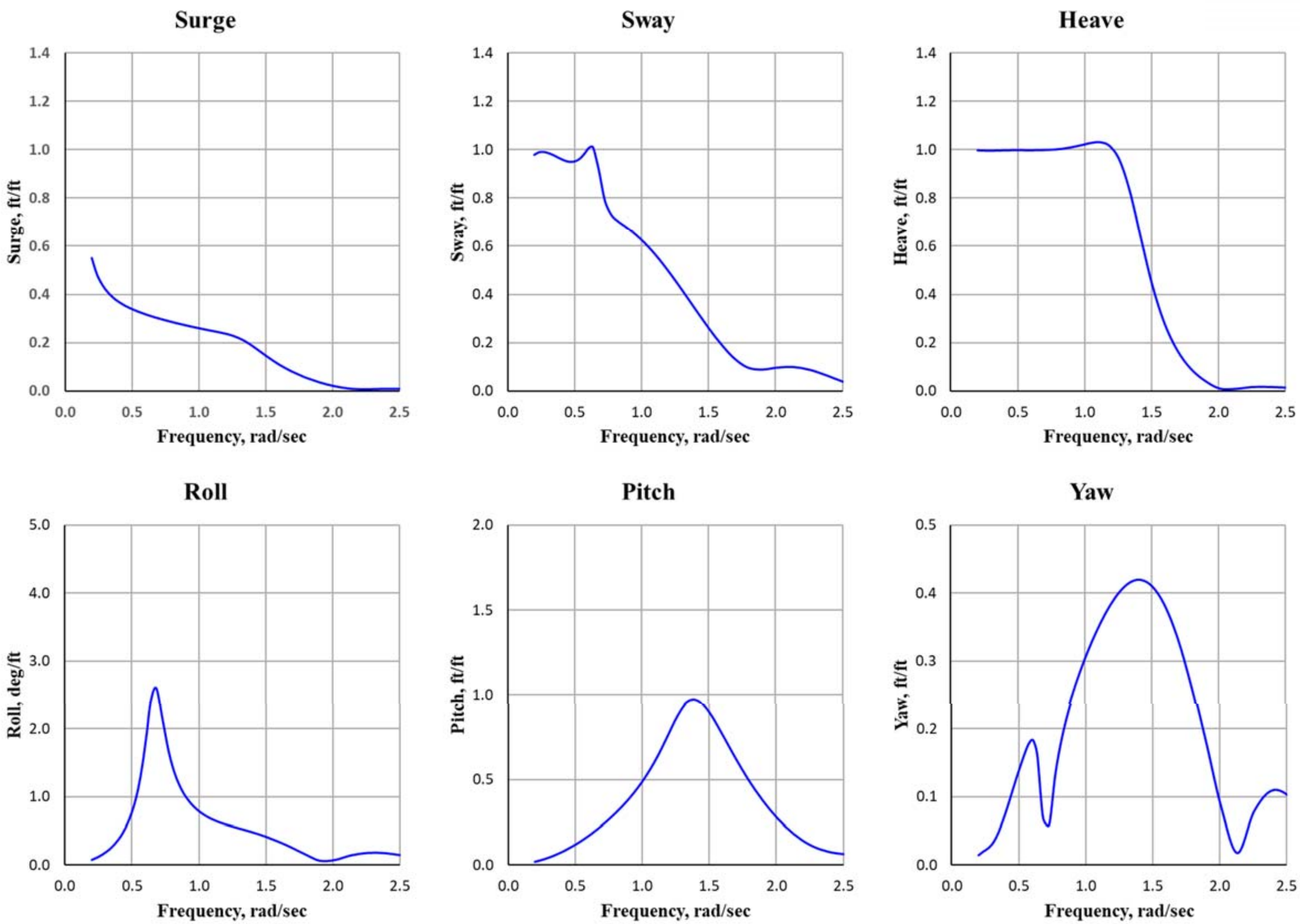
Magnitude of Response Amplitude Operators at Heading = 120 deg



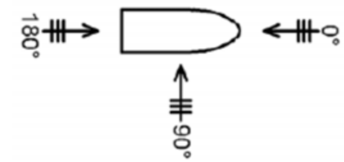


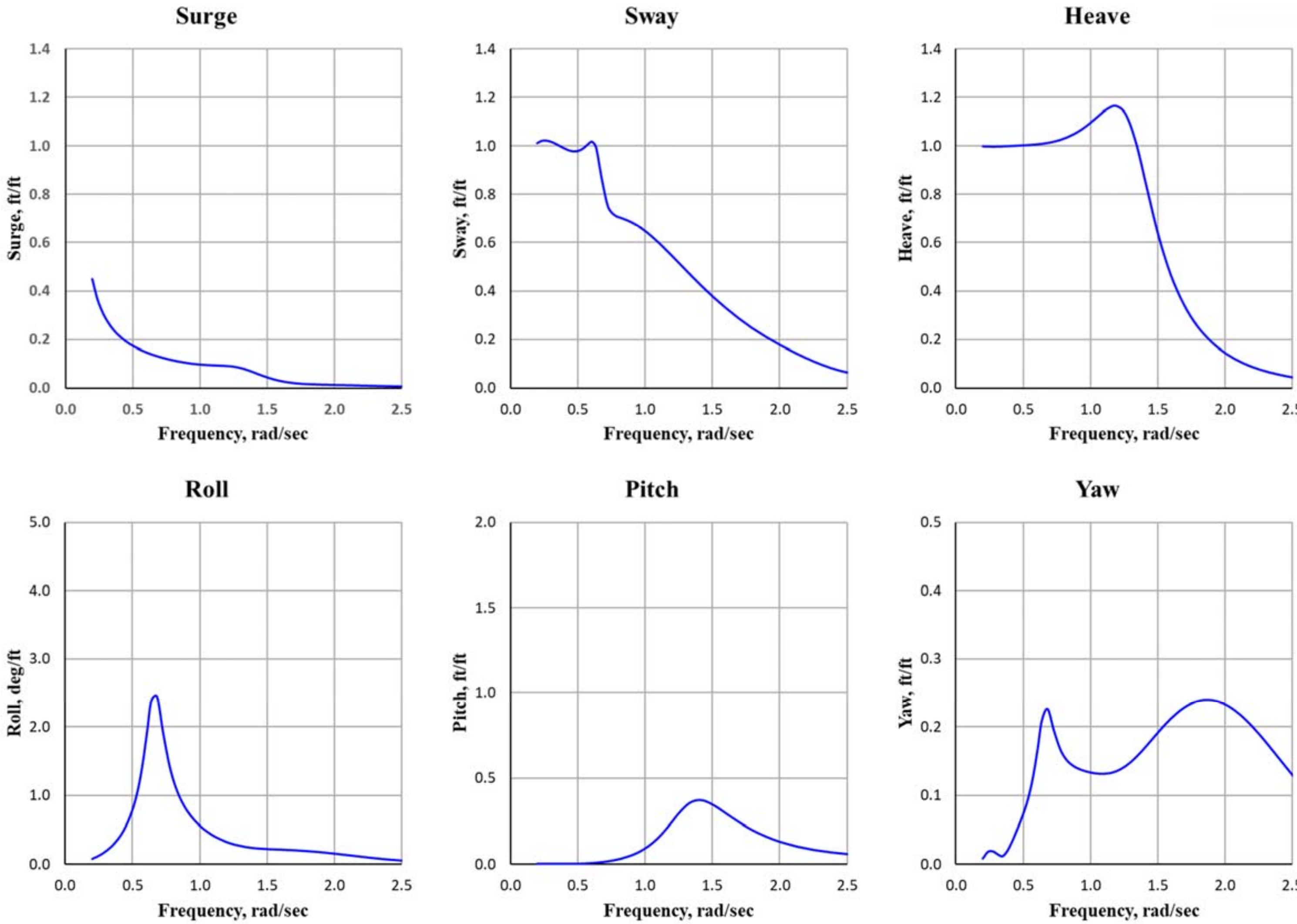
Magnitude of Response Amplitude Operators at Heading = 105 deg



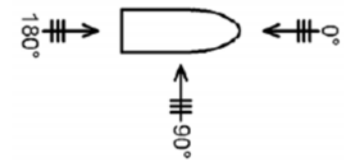


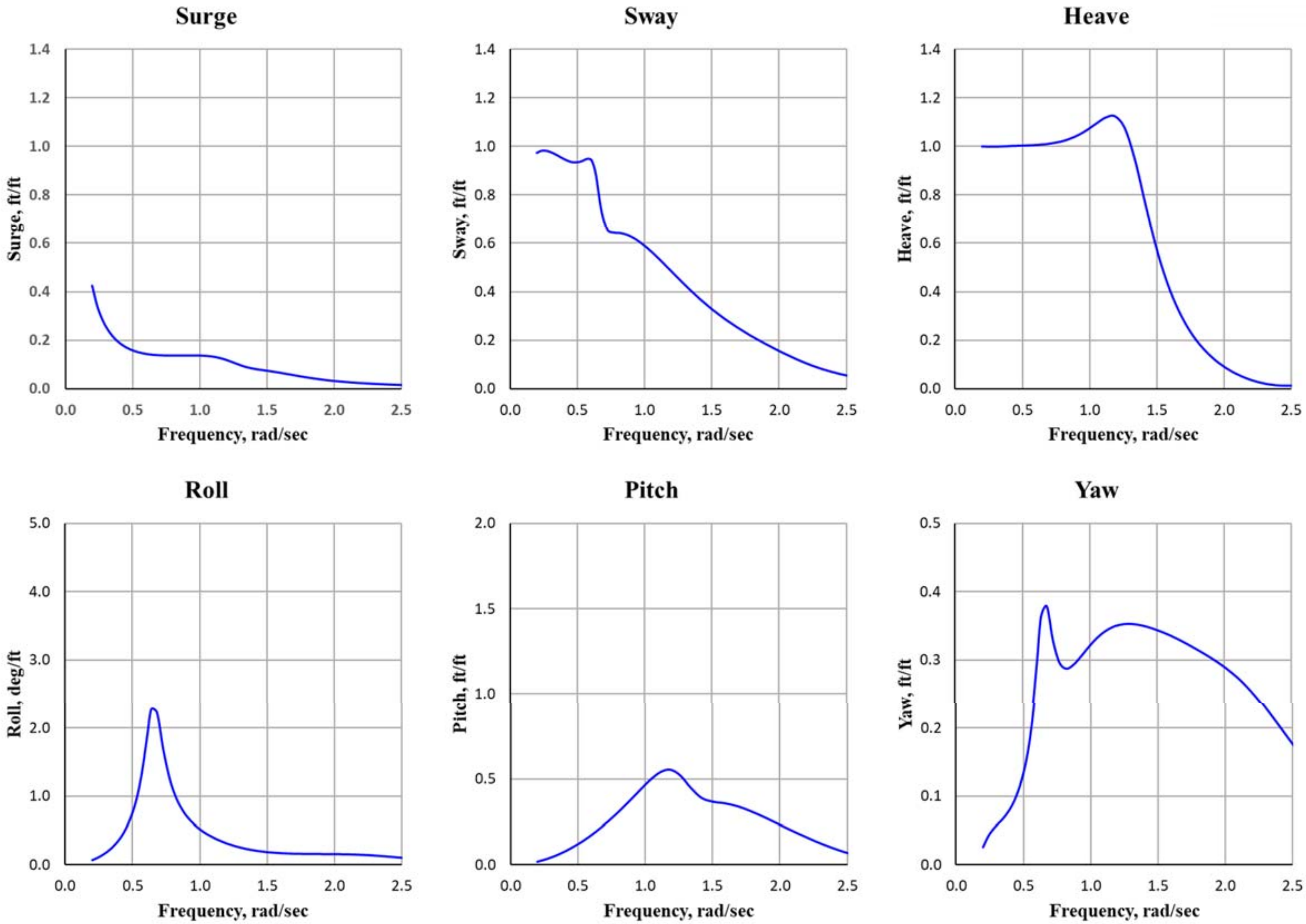
Magnitude of Response Amplitude Operators at Heading = 90 deg



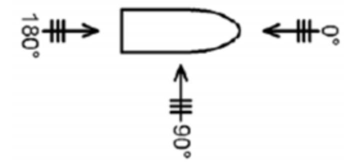


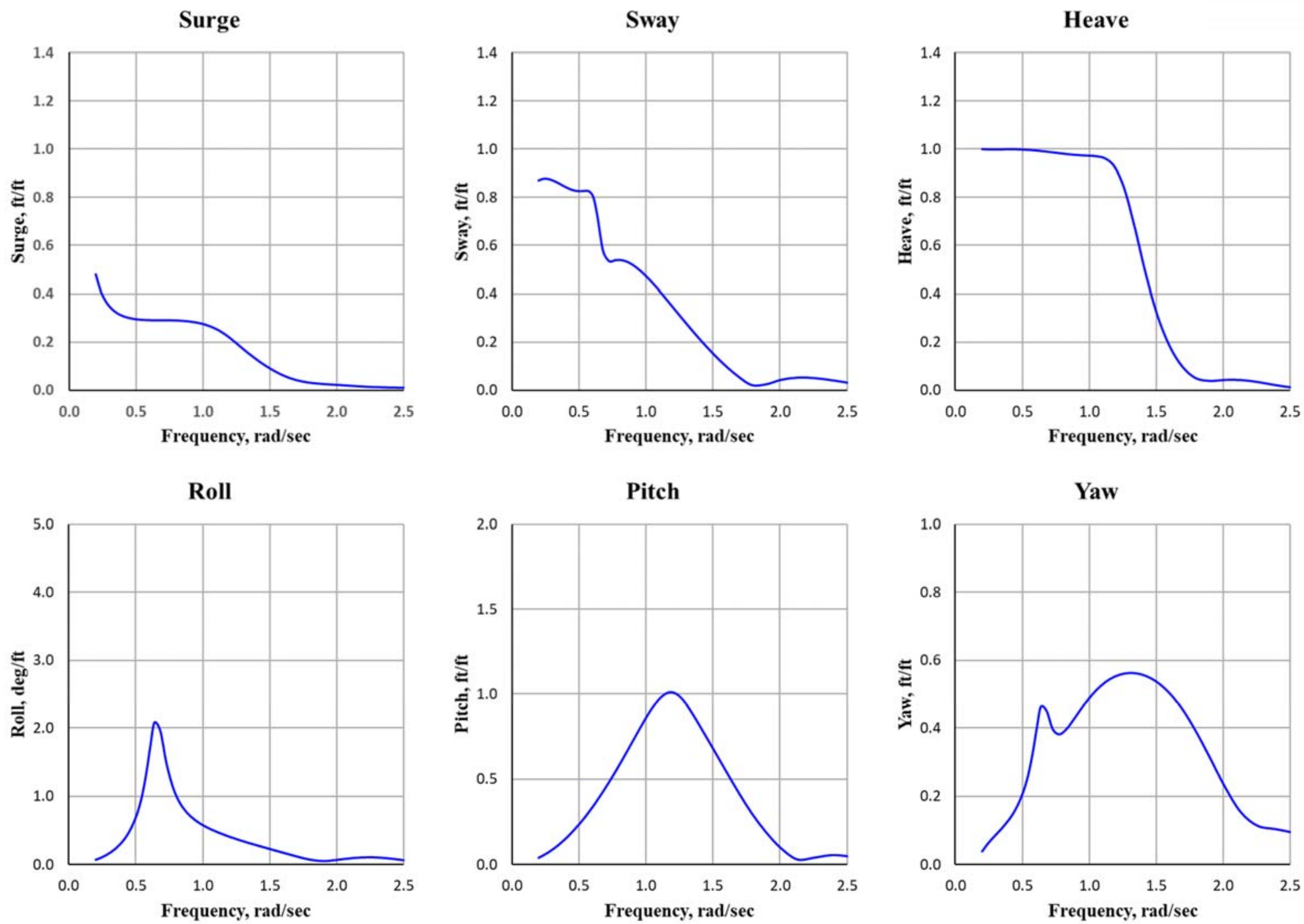
Magnitude of Response Amplitude Operators at Heading = 75 deg



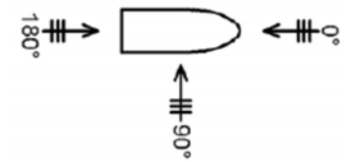


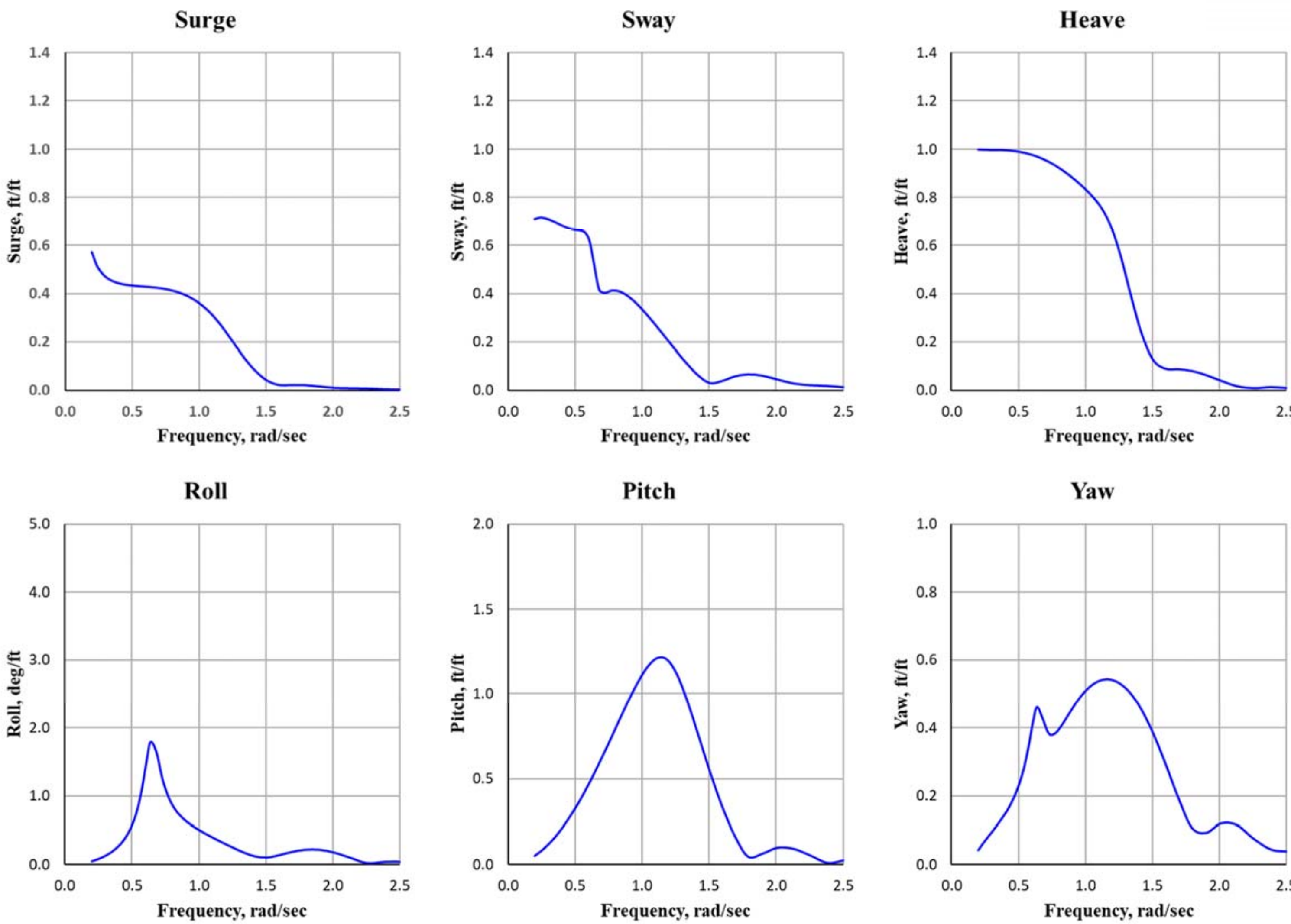
Magnitude of Response Amplitude Operators at Heading = 60 deg



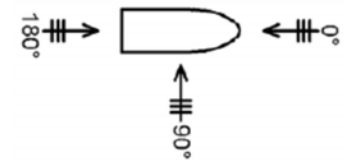


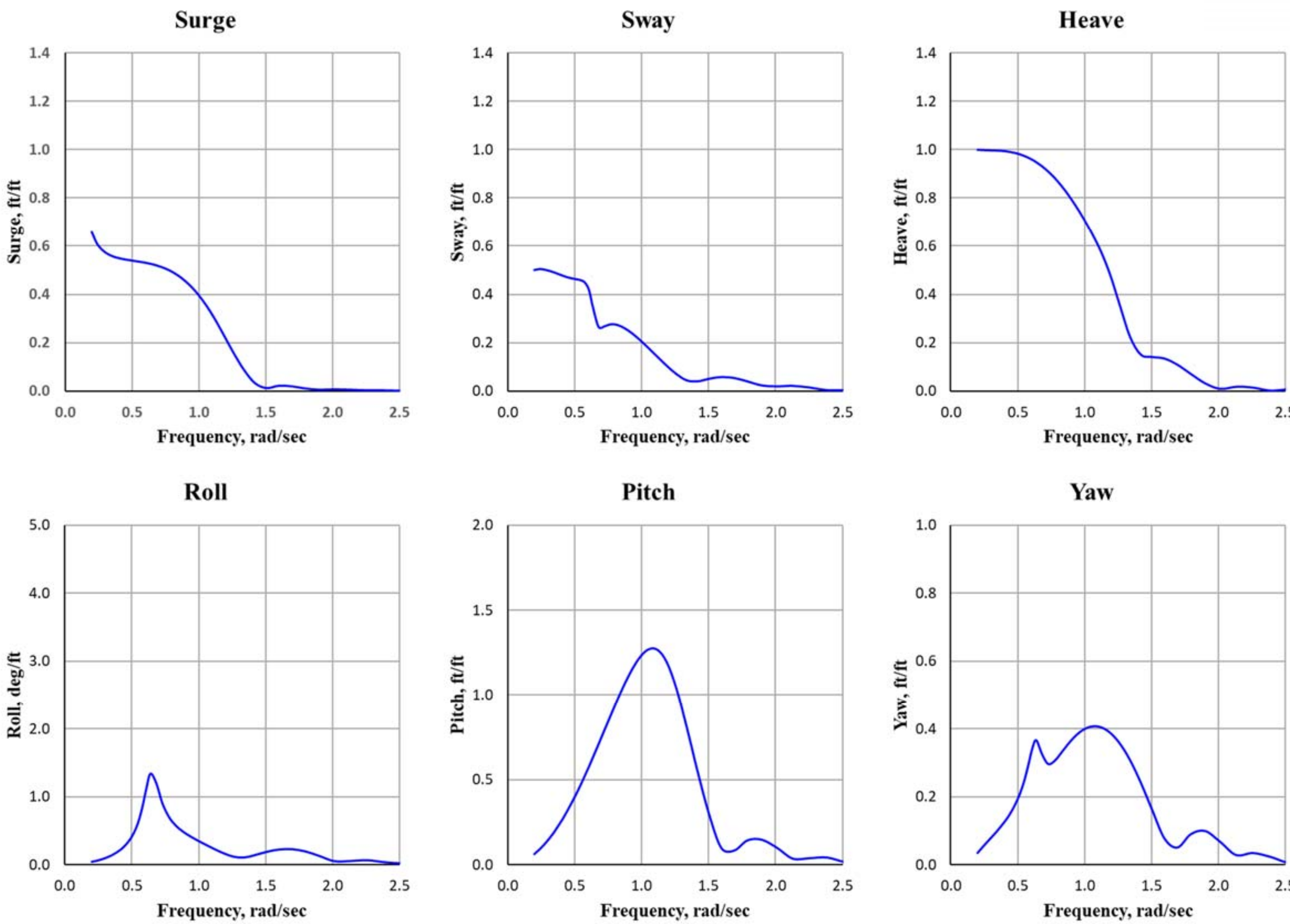
Magnitude of Response Amplitude Operators at Heading = 45 deg



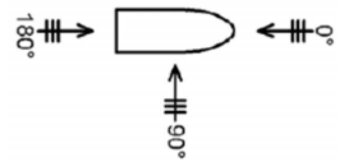


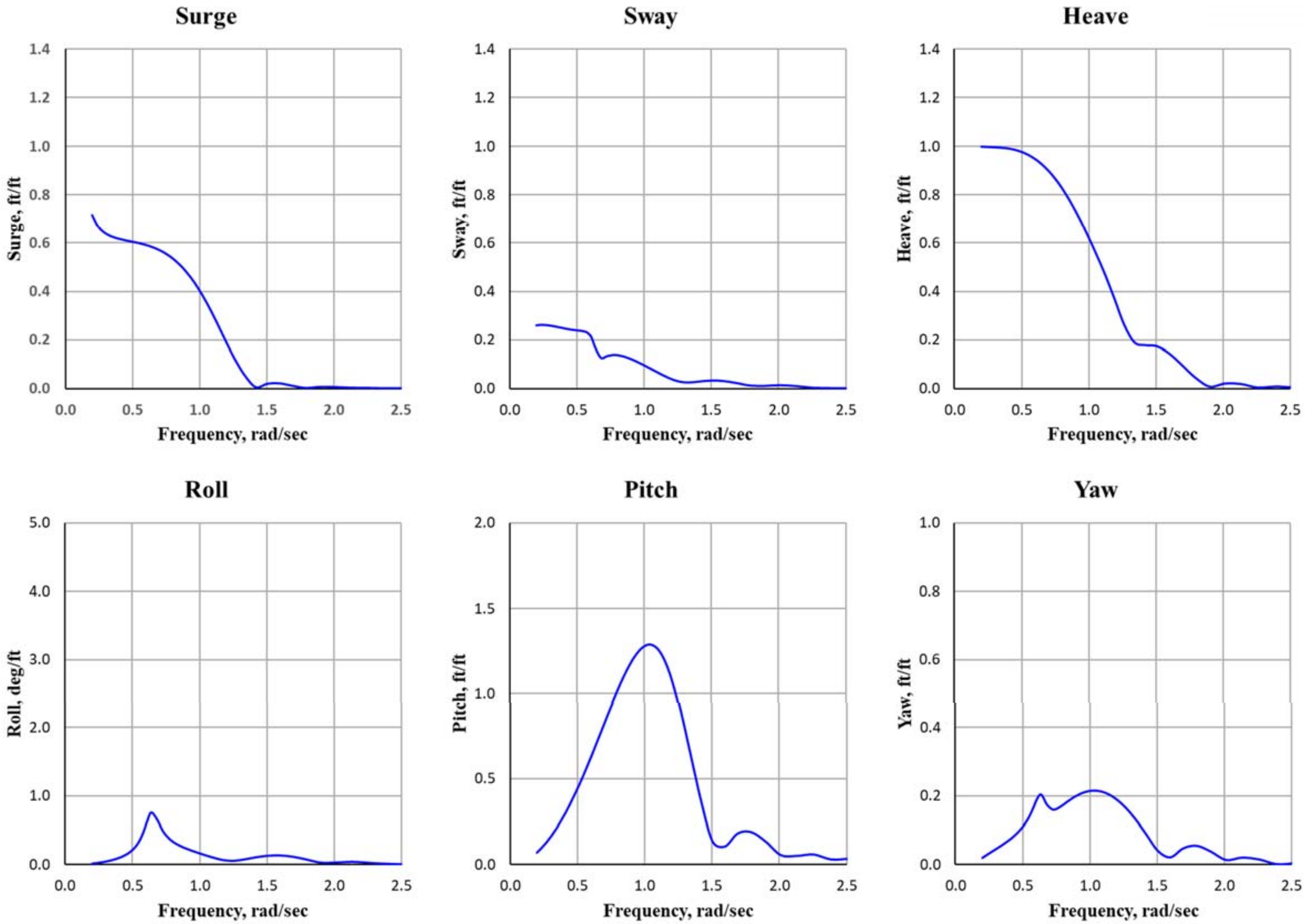
Magnitude of Response Amplitude Operators at Heading = 30 deg





Magnitude of Response Amplitude Operators at Heading = 15 deg





Magnitude of Response Amplitude Operators at Heading = 0 deg